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MECHANICAL TESTS OF MACERATED PHENOLIC MOLDING MATERIAL

By William N. Findley*

SUMMARY

Results of mechanical tests of macerated phenolic molding material are reported. These tests were carried out in a room maintained at a constant temperature of 77° F and relative humidity of 50 percent. The following tests were performed: Static tension, compression, torsion, and flexure tests; long-time creep tests at different stresses, tests for time to fracture under long-continued constant load; Izod and Charpy impact tests; bending fatigue tests at different ranges of stress; rotating-beam fatigue tests at different speeds of testing; rotating beam fatigue tests of notched specimens; and torsion fatigue tests.

The static tests were all made at the same rate of strain; and the results of the static tests include values of yield strength, ultimate strength, and modulus of elasticity in tension, compression, and shear (torsion).

The effect of speed of testing on the results of the torsion test is shown; the effect of "conditioning" on the compressive strength is shown; the effect of stress on creep is shown; and the effects of range of stress, speed of testing, notches and different types of loadings on the fatigue strength are shown.

I. INTRODUCTION

1. Purpose of Investigation

The tests reported herein were undertaken because of the fact that macerated phenolic molding materials are being used in applications in which the load-resisting ability of the material is of importance. An example of such an application is the use of this material for aircraft antenna masts. In some of the applications in which this material is used it may be subjected to static loads,

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to repeated loads, and to impact. Static loads of long duration may result in distortion or fracture as a result of creep (references 1 to 7); repeated loads (vibration) may result in a progressive fracture (fatigue) (references 3, 6, 8, 9, 10); impact may result in fracture if the energy-absorbing capacity of the material is too low. Thus it is evident that a knowledge of the ability of the material to withstand these various types of loading is necessary for a rational design of members and for proper selection of material for a specific application.

To date the volume of significant data on mechanical tests of plastics is relatively small. A bibliography of some of the more important work that has come to the attention of the author is given at the end of this report (pp. 31-32). Considerable data are available on static properties and impact properties, and some data are available on creep. However, part of the data which are available cover results of tests which were not carried out under controlled laboratory conditions. No data have come to the attention of the author on fatigue or creep tests of macerated molding material. Few data are available on torsional properties of plastics, and only one investigation of the effect of range of stress on fatigue properties of plastics (reference 3) has come to the attention of the author.

2. Acknowledgments

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These tests were a part of the work of the Engineering Experiment Station of the University of Illinois, Dean M. L. Enger Director, in the Department of Theoretical and Applied Mechanics of which F. B. Seely is head. The author is indebted to F. B. Seely and H. F. Moore for their suggestions and criticism during the conduct of these tests and the preparation of this paper. The fatigue tests reported

in this paper were performed as part of senior theses by J. W. Lessner and W. J. Lindahl under the author's direction. The tension, compression, and torsion tests were a part of a senior thesis by B. J. Farrell performed under the author's direction. Credit is also due Otto Hintz, R. V. Chase, and W. J. Worley, student test assistants for their careful work during the conduct of these tests.

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II. TYPES OF TEST

The following tests were performed on the phenolic molding material under conditions of constant temperature and constant relative humidity; short-time "static" tests in tension, compression, and torsion were conducted to determine the ultimate strength, yield strength, and modulus of elasticity under the three conditions of loading; tension tests of hollow and solid specimens were conducted at several speeds of testing to determine the effect of speed on the results of static tests; compression tests of specimens subjected to three different "conditioning" procedures were conducted to study the effect of conditioning on the results of tests; Charpy and Izod impact tests were conducted; creep tests and tests for time to fracture under a constant load were conducted at different stresses; bending fatigue tests were conducted to determine the effect of different ranges of stress on the fatigue strength; rotating-beam fatigue tests were conducted to study the effect of speed of testing and the effect of notches on the fatigue strength; and fatigue tests in torsion were conducted to determine the fatigue strength under this type of loading.

III. MATERIAL AND SPECIMENS

1. Material

The "macerated" phenolic molding material for these tests was supplied by the Plastics Division of the Monsanto Chemical Company. It was made in the Monsanto laboratories especially for these tests and was a special formulation as described below. The composition and treatment, however, are similar to Monsanto Resinox 6542 and Resinox 6754. It is also equivalent to U.S. Navy type CFI-20 Bureau of Ships Ad Interim Specifications 1724 (INT).

The molding composition contained 50 percent of a one-stage phenol-formaldehyde resin and 50 percent of cotton denim and twill rag, cut in 3/4-inch pieces. The "cabinet closing time" (a measure of plasticity) was 70 to 80 seconds. The material was preformed at 25° C and 7000 pounds per square inch. Two separate preforms were used per molded slab in order to obtain the required thicknesses.

Sheets, 5- by 7-inch, were molded of this material in two thicknesses, namely, 0.3 inch and 0.5 inch. The different thicknesses were used in order to accommodate the specimens mentioned below. The 0.5-inch slabs were molded 35 minutes at 170° C and 7000 pounds per square inch. The 0.3-inch slabs were molded 15 minutes at 170° C and 7000 pounds per square inch. These molding conditions were established by preliminary experimentation at the Monsanto Laboratory.

2. Specimens

The specimens used in these tests were machined from 5- by 7-inch sheets of the macerated molding material described above. All tension, compression, flexure, creep, time to fracture, bending fatigue, and torsion fatigue specimens were made from sheets approximately 0.3 inch thick. The torsion, impact, and rotating-beam fatigue tests were made on specimens cut from sheets 0.5 inch thick. Tension, compression, torsion, flexure, time to fracture and creep specimens were cut from the sheet with the axis of the specimen parallel to the 7-inch dimension of the sheet. All fatigue and impact specimens were cut with their axes parallel to the 5-inch dimension. Insofar as possible all specimens for one group of tests were cut from one sheet. Where this was not possible the sheet numbers were indicated on the curves.

The specimens were machined to the dimensions shown in figures 1, 2, and 3 by milling or turning, as required, using sharp tools and such combinations of tool shape, speed, and feed as gave good finish and a minimum of heating of the specimen. After machining, all machined edges were smoothed with emery paper. A high polish was not possible because of the cloth filler in the material.

3. Preconditioning of Specimens

All specimens were allowed to remain in the air-conditioned laboratory for at least two weeks after machining before the tests were started. All tests were carried out in a laboratory which was maintained at a constant temperature of $77^{\circ} \pm 1^{\circ}$ F, and 50 ±2 percent relative humidity continuously throughout the duration of the tests. This was necessary because of the sensitivity of the material to small changes in temperature and relative humidity.

IV. APPARATUS AND TEST PROCEDURE

1. Static Tension Tests

The tension tests were made on specimens shown in figure 1a. These specimens were held in Templin wedge grips and tested in a Riehle 1500-pound single-screw machine modified to provide pendulum weighing and equipped with a device for semiautographic recording, shown in figure 4. All specimens were tested at a head speed of 0.04 inch per minute. This speed resulted in a rate of strain of 0.0015 inch per minute. A Moore-Hayes 2-inch extensometer was attached to the specimen and readings of load, extensometer division, and time were taken during the tests.

2. Static Compression Tests

The same machine was used for compression tests as for tension tests except that a compression tool, shown in figure 4, was used with the former in order to avoid the possibility of eccentric loading of the compression specimens. In this instrument the specimen A, figure 4, was compressed between the upper platten B and the cylinder C. The cylinder was guided in the yoke D so that the face of the cylinder was always parallel to the upper platten. Thus, if precautions are taken to machine the specimen ends parallel and center the specimen on the cylinder, the amount of eccentric loading should be negligible. Compression tests were made on two sizes of specimen cut from the same sheet 0.3 inch thick, as shown in figures 2a and 2b. The short specimens, l/r of 12, were used to obtain the compressive strength of the material; whereas the longer specimens, l/r of 27, were used to determine the modulus of elasticity of the material and the general shape of the stress-strain curve. The term l/r indicates the ratio of the length of the specimen to the radius of gyration of the cross section of the specimen. In order to obtain the modulus of elasticity and shape of the stress-strain curve a compressometer of 1-inch gage length was used with the longer specimens. For the long specimens all tests were run at a head speed of 0.0105 inch per minute (rate of strain of 0.0015 in. per in. per min.).

3. Static Torsion Tests

It was necessary to design and build special apparatus for this test because machines of low capacity were not available. The apparatus used is shown in figure 5. The pendulum weighing system of the tension machine was used as the measuring device for the torsion machine. This was accomplished by attaching to the tension machine a twisting head A in figure 5, driven by a double worm drive. A special chuck B was attached to the shaft of this twisting head and another chuck C to the axis of the pendulum D. These chucks were designed to apply a torque to the specimen with little danger of bending the specimen at the same time. This was accomplished by mounting the specimen on centers and applying the torque as a couple by means of adjustable screws.

The detrusion gage, used for measuring the shearing strain, is shown in figure 6. It was designed to accommodate materials whose ultimate shearing strain was relatively small and materials which might twist two or three revolutions in a length of 2 inches. The instrument consisted of two rings A in figure 6, which are slipped over the specimen and fastened to it by three adjusting screws in each ring. A gage length of 2 inches was obtained by use of a removable spacer B. To one of the rings was fastened a circular scale C for measuring large detrusion. Two 10-inch arms, D, fastened to the same ring carried scales on the end which were used in measuring small detrusion. Adjustable pointers E were attached to the other ring in such a way as to indicate the readings on their respective scales.

The procedure in conducting a torsion test was first to mount the detrusion gage, then affix the torque arms F, in figure 6, to the specimen, mount the whole between the centers of the torsion machine, and adjust the torque screws. The driving chuck was then rotated at a uniform speed and readings of detrusion, torque, and time were taken at intervals of detrusion until fracture took place.

The shearing stress was computed from the equation $\tau = \frac{Tc}{J}$ and shearing strain was computed from the relation $\gamma = \frac{c\,\theta}{l}$.

4. Creep Tests

The equipment used for conducting the creep tests consisted of a steel rack, from which 24 specimens could be suspended; calibrated weights used for loading the specimens; measuring equipment for determining the strain in each specimen; and a clock equipped with a counter to record the elapsed time in hours.

Figure 7 shows a portion of the creep rack with apparatus set up for measuring the strain of a specimen. The specimen A was subjected to an axial tensile load by means of dead weights attached to the rod B. The specimen was held by grips C, which contained a hook-and-eye type of swivel joint. This joint was provided in order to minimize the possibility of bending the specimen.

The extensometer used for measuring the creep consisted of a lever-type instrument with a traveling microscope (cathetometer) D, figure 7, for measuring the displacement between fixed reference marks on the end of the lever E and the stationary arm F. A track was provided for the microscope so that it could be moved from specimen to specimen quickly.

The gage length of the extensometer was 4 inches and the lever ratio was 10 to 1. One end of this lever was forked and fastened by pivots to the lower clamp attached to the specimen, figure 7. The axis of this pivot passed through the centroid of the cross section of the specimen. (The pin itself did not go through the specimen.) Thus the strain measured by this instrument was the average strain in the specimen and it was not necessary to average the results of two instruments fastened to opposite sides of the specimen. The fulcrum of the lever was pivoted to a rod whose other end was fastened to the upper clamp on the specimen. A spring clip G, figure 7, was used to attach this rod to the upper clamp so that the extensometer could be left on the specimen during fracture, if necessary, without damage to the instrument.

Each instrument was calibrated against a micrometer screw before use. Flat clamps were used to attach the extensometers to the specimens instead of pointed screws because creep of the material might cause screws to sink into the specimen, thus causing early fracture. The distance between the centers of the flat clamps was considered to be the gage length of the extensometer. A uniform gage length for each specimen was essential for accurate comparison of tests. This uniformity was obtained by using identical extensometers and a jig to assemble the extensometers to the specimen, figure 8.

Ten specimens milled as shown in figure 1b were tested at various stresses ranging from 1400 to 3700 pounds per square inch. The procedure in starting the tests was as follows:

The weights, weighing from 75 to 150 pounds, were first supported on planks, blocked up in such a way that they could be used as levers to lower the weights quickly but gently until they were supported by the specimen. Before lowering the weights, the initial extensometer readings were obtained with the traveling microscope. Then the weight was lowered on the specimen, the extensometer was immediately read again, and the time was recorded. The difference between the strain computed from these two sets of readings was the elastic strain. Any further increase in strain was the result of creep. Readings of strain and time were taken at intervals of time, which for the high-stress tests were from 2- to 12-hour intervals until fracture. Low-stress specimens were read about every two days for a month, then every one to two weeks.

5. Fracture Under Long-Continued Constant Load

This test was undertaken to determine the time required to cause fracture as a result of creep under a tension load maintained at a constant value throughout the test. The specimens used were turned on a lathe to the dimensions shown in figure 2c. The apparatus for the tests consisted of a steel rack from which the specimens were suspended and loaded in tension by hanging sufficient weight from the specimen to produce the desired stress. This weight remained hanging on the specimen until the specimen broke, at which time the falling of the weight would release a catch to stop a clock and thus record the time of fracture.

6. Impact

An Olsen 25-inch-pounds impact testing machine was used for these tests. It was equipped for either Izod or Charpy type of test. Specimens for these tests (figs. 1c and 1d) were machined from two different sheets of material, with the axes of the specimens parallel to the 5-inch dimension of the sheet. Four Izod specimens were cut from each sheet with the notch parallel to the surface of the sheet, and four specimens with the notch perpendicular to the surface of the sheet. Likewise, four Charpy specimens were cut from each sheet with notch parallel to the surface of the sheet, and three specimens with notch perpendicular to the sheet. All specimens were prepared at the same time and tested at the same time under the usual procedure. The energy absorbed by the specimen during the test was measured.

7. Fatigue Tests

(a) Bending.- Fatigue tests in bending were conducted on fixed-cantilever, constant-amplitude fatigue machines. In this type of machine (fig. 9) the specimen A was repeatedly bent back and forth as a cantilever beam by the variable eccentric B. Both horizontal and vertical adjustment of the relative position of the spindle of the machine and the specimen vise was provided to allow a variety of different tests. The machines were equipped with a V-belt drive to provide variable speed as shown in figure 9.

The procedure used in conducting these tests is described in the A.S.T.M. Tentative Standard for Repeated Flexural Stress (Fatigue) Test of Plastics.* In all cases the stress in the specimen (fig. 3a) was computed from the equation $\sigma = \frac{Mc}{I}$. The bending moment M was obtained

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*A.S.T.M. designation: D671 - 42T, "A.S.T.M. Standards, Including Tentative Standards," Part III, 1942, p. 1251. This method was prepared by the A.S.T.M. section on Fatigue and Repeated Impact Tests of Plastics, of which the author was chairman. The method was based on experience gained largely during the conduct of the tests reported in this paper and previous work by the author on cellulose acetate.

from a calibrated dynamometer C, and the number of cycles to which the specimen was subjected was recorded by a counter D. For each specimen placed in the machine the stress corresponding to the deflection of the specimen during the test was calculated from the bending moment measured while the machine was at rest. The number of cycles for fracture was also obtained. These data were then plotted with stress as ordinate and number of cycles as abscissa, using semilog plotting.

In testing the phenolic molding material it was found that the specimen never completely fractured in the bending fatigue machine. Fatigue cracks formed but the cloth filler prevented complete separation of the two ends of the specimen. Because of this fact, it was necessary to devise a special mechanism to shut off the machine when the specimen became cracked. This mechanism consisted of a spring dynamometer together with an electrical contact to close the circuit of a sensitive relay and stop the machine when a fatigue crack caused the maximum load on the dynamometer to become smaller than the original section by a predetermined amount (about 25 percent).

(b) Torsion.- The machine used for torsion fatigue tests was of the constant-amplitude type and was constructed from a machine of the bending type by the addition of certain parts, as shown in figure 10. An arm A was attached to the bending-type machine so as to support the fixed end of the torsion specimen B and the dynamometer C with its dial D. For the torsion tests, the specimen B was fastened at an angle to the lever arm E attached to the connecting rod F. With the choice of the proper angle the bending moment at the minimum section of the specimen could be made zero, so that the only significant stress at the minimum section was a torsion stress. There was a slight horizontal-shear stress which was negligible compared to the stresses resulting from torsion. The connecting rod F was fastened to the lever arm E through a universal joint to allow freedom of motion.

The dynamometer was calibrated in terms of force at the wrist pin of the connecting rod as in the case of the bending tests. Shearing stress was computed from the equation $\tau = \frac{Tc}{J}$. The stress was adjusted by means of the variable eccentric as in the case of the bending tests.

(c) Rotating beam.- The rotating cantilever-beam fatigue testing machines were as shown in figure 11. The specimen A was held in the end of the spindle B by means of a split collet. An extension shaft C was fastened to the other end of the specimen by means of a collet machined integral with the shaft. A load was applied to the end of this shaft through a small ball bearing. A beam and poise D was used to apply this load. The entire shaft assembly was rotated by a motor through a belt. A counter E was attached to record the number of cycles, and a microswitch was used to stop the machine when a crack had formed in the specimen. Stress at the minimum section was computed from the equation $\sigma = \frac{Mc}{I}$ in which M was obtained from the load applied through the poise. Machines of this type were found to offer some difficulty due to vibration with nonhomogeneous material such as phenolic molding material.

V. RESULTS OF TESTS

1. Static Tension Tests

In figures 12A,B,C are shown the stress-strain curves for tension tests of the phenolic molding material. Figure 13 shows the strain-time curve corresponding to the stress-strain curve of figure 12C. From these curves the following quantities were measured: yield strength at 0.05 percent offset, ultimate strength, ultimate strain, modulus of elasticity, and rate of strain. (See appendix for definition of the terms used in this report.) The values obtained for these quantities are tabulated in table I for the five specimens tested.

The average modulus of elasticity (slope of the initial portion of the curve) was 981,000 pounds per square inch for the five specimens. The average yield strength for 0.05 percent offset from the initial tangent line was 4010 pounds per square inch. An offset of 0.05 percent was chosen because specimens occasionally fractured before any larger offset was reached. The ultimate strength was only slightly higher, 4550 pounds per square inch, and the average ultimate strain (at fracture) was 0.00543 inch per inch. The average rate of strain was 0.0014 inch per inch per minute (no load head speed of 0.040 in. per min.). The rate of strain was obtained as the slope of the strain-time curve in the region just before the strain for which strain was no longer proportional to stress, that is, the slope of the diagonal line in figure 13.

It was noticed that there was not a constant relation between the measured strain and the time (fig. 13). This curve may be approximately divided into three portions by the lines representing strains of 0.001 and 0.003 inch per inch. The first portion was curved, due probably to friction lag in the extensometer or perhaps also to slippage of the wedge grips or other readjustments of the machine under load; the second portion was approximately a straight line corresponding to the straight-line portion of the stress-strain diagram; the third portion was curved. This was due to the fact that stress was not proportional to strain during this portion of the strain-time curve. As a result of this fact the load on the machine no longer increased at a constant rate, so that the machine no longer deflected as much for the same amount of motion of the loading screw. Therefore the specimen must stretch more in the same time interval. A stiffer testing machine would probably give a more nearly straight strain-time curve. The ratio of load to deflection under a tension load was 10,170 pounds per inch for this machine.

The data shown in table I were taken from specimens cut from two different 5- by 7-inch sheets. (The figures before the letter in the specimen number designate the number of the sheet.) An examination of these data and those for the impact tests in table V shows that there was no marked difference in properties of different sheets.

The average deviation from the mean is also shown in table I. It is a measure of the amount of scatter in the data. The small scatter evident in table I is probably fortuitous since the results of other tests indicate a greater scatter, as might be expected with such a nonhomogeneous material. A typical fractured specimen is shown in figure 33a.

2. Static Compression Tests

In figures 14A, B, C, D are shown the stress-strain curves for compression tests of specimens shown in figure 2a. Specimens 2 inches in length were used for these tests to permit the use of a compressometer having a 1-inch gage length. The data plotted in figure 14A were taken with a compressometer having a 1-to-1 lever ratio and a 0.0001 Last-Word dial. This dial did not have sufficient travel to cover the entire range of strains, but was used to obtain data at the foot of the curve for use in determining the modulus of elasticity. The data plotted in figures 14B,C,D were obtained with a similar instrument equipped with a 0.001 dial so that strain readings could be taken to fracture.

Table II summarizes the data from all of these curves and includes average values and average deviations from the mean. The average modulus of elasticity in compression was 886,000 pounds per square inch. It was noticed that there was about twice the spread in values of modulus for the compression tests as for the tension tests, and that there is just as much spread between results obtained with the 0.0001 dial as with the 0.001 dial. The average value of modulus obtained in compression was about 10 percent less than the average value obtained in tension.

The average value of yield strength at 0.05 percent offset was 4120 pounds per square inch, which is about 3 percent higher than the corresponding value in tension. The yield strength at 0.2 percent offset was also obtained for the compression tests. The average value was 6060 pounds per square inch. The average ultimate strength obtained in these tests was 13,200 pounds per square inch. This value was not considered representative because the length of the specimen was such as to permit buckling to occur before failure. There was, however, not sufficient tendency for buckling to affect the values of yield strength reported above. Because of buckling, another set of shorter specimens, as shown in figure 2b, was tested. The results are tabulated in table III. The average value of ultimate strength for these specimens was 18,960 pounds per square inch, which was about four times the ultimate strength in tension.

Figure 15 shows a sample strain-time curve with a diagonal line drawn to indicate the slope, corresponding to the elastic region of the stress-strain curve. The same characteristics are observed in this curve as in the tension strain-time curve, figure 13.

Fractured specimens of both the long and the short type are shown in figures 33b,c. The diagonal planes of failure suggest that the fracture resulted from a shearing stress.

For purposes of comparison the rate of strain was made approximately equal in the tension and compression tests. It was 0.0015 inch per inch per minute (head speed of 0.0105 in. per min.) for the "long" compression test.

In the case of the short specimens the rate of strain was determined by comparing the load-time data, taken for these tests (not shown), with load-time data for the "long" specimens.

It will be noticed that the head speed for the compression tests was about one-fourth the head speed for the tension tests, although the rate of strain was the same and the machine was the same for both tests. This difference resulted largely from the difference in shape of the specimen and method of gripping the specimen. It is thus evident that care must be exercised in the selection of testing-machine speeds if results of tension and compression tests of plastics are to be comparable. This precaution is, of course, not necessary with materials for which the test data are not affected by changes in rate of strain.

3. Static Torsion Tests

In figure 16 are shown shearing stress against shearing strain curves as obtained from torsion tests of "solid" specimens (fig. 2e) of phenolic molding material. The curves for the torsion tests are similar to those for the tension tests in that fracture occurred after a relatively small amount of strain. The last two curves show a straight-line stress-strain relation up to about 2000 pounds per square inch; whereas, the first curve in figure 16 indicates some deviation from linearity at the lower region. This was attributed to the fact that a spacing ring used in setting up the detrusion gage was accidentally left on, causing slight friction. From these curves values of modulus of elasticity in shear, yield strength at 0.05 percent and 0.2 percent offset, and torsional modulus of rupture were obtained. These values are tabulated in table IV. The average value of yield strength at 0.05 percent offset was 2550 pounds per square inch. This was about 63 percent of the yield strength at 0.05 percent offset in tension and compression. The average yield strength at 0.2 percent offset was 3290 pounds per square inch, which was about the same percentage increase over the 0.05 percent offset as observed for the compression tests. The average modulus of rupture was only slightly higher than the yield strength for 0.2 percent offset and was 3330 pounds per square inch. The ultimate strain was about three times the ultimate strain in tension and about one-third the ultimate strain in compression. The average modulus of elasticity in shear was 234,000 pounds per square inch, which is 25 percent of the average of tension and compression modulus. The shear rate of strain as shown in table IV was obtained from strain-time curves such as the curves shown in figure 17. It will be noticed that the shearing strain-time curve does not show the first "stage" observed in the tension and compression tests; that is, there was no period of adjustment required for the detrusion gage to overcome friction lag as was the case with the extensometer and compressometer. This was true because of the construction of the instrument which involved no frictional load on the measuring arms.

The rate of strain in tension which occurred during the torsion test was obtained from the known relationship that the maximum tensile stress equals the maximum shearing stress in a circular member subjected to torsion. From this fact the relationship between the rate of strain in tension and the rate of strain in shear was computed from the formula $\frac{\epsilon}{t} = \frac{\gamma}{t}\frac{G}{E}$, where $\frac{\epsilon}{t}$ is the tensile rate of strain; $\frac{\gamma}{t}$ is the shearing rate of strain; and $\frac{G}{E}$ the ratio of shearing modulus to tensile modulus. It will be noticed that the tensile rate of strain in the torsion tests was approximately equal to the tensile rate of strain in both the tension test and the compression test. This was purposely done in order that the three tests would be on a comparable basis. It was necessary to use the same rate of strain for comparative purposes because it was known that the rate of strain affected the values of yield strength, ultimate strength, modulus of rupture, and so forth. (See figs. 18, 19, and the next paragraph.)

4. Effect of Speed of Testing on the Results Obtained from the Torsion Test

Torsion tests were performed at several speeds of testing to study the effect of speed of testing on the properties measured in the torsion tests. During these tests, readings of torque, angle of twist, and time were taken. From these data the shearing stress and shearing strain were computed. The shearing stress was plotted against shearing strain in figure 18 for tests of "solid" specimens at rates of strain from 0.0004 to 0.029 inch per inch per minute. The shearing rate of strain was obtained in the same manner as described above.

It was observed that the stress-strain diagram deviated from a straight-line relationship at a lower value of stress for the slow rates of strain than for the high rates of strain. This deviation was probably the effect of creep taking place at the lower rates of strain.

In order to obtain a better picture of the effect of changing the rate of strain on the results of the torsion tests, the shearing yield strength at 0.05 percent offset was obtained for each of the curves shown in figure 18. (The auxiliary line represents an offset of 0.05 percent.) The shearing yield strength was plotted against the shearing rate of strain in figure 19. The data reported for the torsion tests in table IV were also plotted on this diagram. It was observed that the shearing yield strength increased rapidly with increase of rate of strain at relatively low rates of strain. Above a rate of strain of about 0.01 inch per inch per minute the shearing yield strength was relatively little affected by further increase in rate of strain. This effect of rate of strain was similar in trend, but not in degree, to the effect of rate of strain on the tension test of cellulose acetate (reference 7).

Tests were also performed on hollow torsion specimens (fig. 2f). The shearing stress obtained from tests of the hollow specimens was plotted against shearing strain in figure 18. These tests were undertaken in an attempt to correlate the results of the torsion tests with the results of the tension tests of the same material. It was expected that the hollow torsion test would correlate much better than the solid torsion test, because the equation

$$\tau = \frac{Tc}{J}$$

would yield a more accurate value of stress in the case of the hollow specimen than in the case of the solid specimen for values of stress near fracture. The average value of the maximum stress occurring in the hollow specimen was about 2000 pounds per square inch or about one-half of the tensile strength. (See table I.) This may possibly be due to the fact that the fracture started at a position on the surface of the specimen which was originally at the interior of the sheet. Also the tensile stress at the point of fracture was at an angle to the plane of the original sheet rather than parallel to the sheet as in the case of the tension test, so that some difference in strength might be expected.

The crack progressed along a helix, indicating that the significant stress causing fracture was probably a tension stress. (See figs. 33d,e.) Elementary theory shows that the maximum tension stress in a member subjected to torsion is equal to the maximum shearing stress, so that the values of maximum shearing stress obtained from the torsion test of a hollow specimen should be nearly equal to the tensile strength of the same material as obtained in a tension test, instead of one-half the tensile strength.

The hollow specimens were tested at several different rates of strain as were the solid specimens. Results of the former, however, do not correlate well - probably because of the fact that the size of the discontinuities in the material itself were the same order of magnitude as the wall thickness of the hollow section.

No measurable variation in shearing modulus of elasticity with change in rate of strain was observed. The modulus of elasticity in shear as obtained from the average slope of the curves shown in figure 18 was 290,000 pounds per square inch. The value reported above for the other set of tests was 234,000 pounds per square inch. The difference between these two values is possibly due to the fact that the specimens in the two tests were obtained from different sheets. All specimens used for the solid tests shown in figure 18 were obtained from the same sheet.

5. The Effect of Initial Conditioning on the Compressive Strength and the Specific Weight

Three groups of 25 compression specimens each (fig. 2b) were prepared from the same sheet of material. Each group of 25 was subjected to a different conditioning procedure. One group was immersed in water for 48 hours, the second group was placed in a desiccator over anhydrous calcium chloride, and the third group was placed in an oven at a temperature of 122° F for 48 hours, then removed to a calcium-chloride desiccator for 24 hours. Immediately after the specified conditioning time, all of these specimens were placed in a room maintained at a constant temperature of 77° F and constant relative humidity of 50 percent for the duration of the tests. Two specimens from each group were set aside as control specimens and were weighed and measured at intervals of time. Immediately after the specimens were removed from the conditioning medium, one of each group was tested in compression and the ultimate strength recorded. Specimens from each group were then tested at succeeding intervals of time thereafter for a period of about 8000 hours. The control specimens were weighed and measured at the same time that compression tests were performed.

This study was undertaken in order to obtain a quantitative knowledge of the duration of time required for the strength and weight of phenolic molding material to come to equilibrium when the specimens were maintained continuously in an atmosphere of constant temperature and constant relative humidity. Such information was needed in order to determine the conditioning procedure necessary to obtain reproducible results from mechanical tests of plastics.

The change in specific weight with time is shown in figure 20 for the control specimens from each group. It was observed that the specific weight decreased for specimens initially immersed in water; whereas the specific weight increased for specimens initially placed over calcium chloride and also for those initially heated. It was observed that a time of about 1000 hours (41 days) was required to return the specific weight approximately to its initial value (within 5 percent of the change in specific weight caused by immersion for 48 hr).

A similar series of tests of cellulose acetate (reference 8) was carried out simultaneously with this series of tests. The acetate was subjected to two different conditions - immersion and drying over calcium chloride. A comparison of the curves showing change in specific weight with time shows that the behavior of the two materials was almost identical up to a time of 1000 hours. Beyond 1000 hours the specific weight of specimens of both materials which were immersed in water remained substantially constant, but the specific weight of the dried acetate decreased again after 1000 hours while the specific weight of the molding material continued to increase even beyond the weight before drying.

The variation in ultimate strength with the elapse of time after conditioning is shown in figure 21. The strength of the initially wet specimens was observed to increase with time. The strength of the heated specimens decreased with time and the strength of the dried specimens decreased with time. More conclusive results might have been obtained by the use of a larger number of specimens to overcome the effect of the scatter observed in the data.

6. Static Bending Tests (Flexure)

Flexure tests were performed on specimens shown in figure 2d, using the machine shown in figures 4 and 5 for applying the load. A four-point loading system was employed by means of a beam-and-linkage arrangement so as to produce a constant bending moment in the center portion of the specimens. The average result of five specimens showed a modulus of rupture in bending of 8000 pounds per square inch. These tests were performed in such a way that the rate of strain of the extreme fiber was about the same as in the tension and compression test reported in tables I and II - that is, the rate of strain was about 0.0015 inch per inch per minute. The rate of strain for the bending tests was obtained by plotting a stress-time curve. From this curve and the known value of modulus of elasticity the rate of strain was computed. A sample stress-time curve for the bending test is shown in figure 22. These tests show that the modulus of rupture in flexure was about twice the static tensile strength, and about two-thirds the static compressive strength.

7. Impact Tests

Impact tests were made on specimens of both the Charpy and Izod type on specimens (figs. 1c,d) machined from two different slabs. The results of these tests are tabulated in table V. Four specimens of each type from each slab were tested with the V-notch parallel to the molded surface of the sheet, and four specimens of the Izod type and three of the Charpy type were machined with the V-notch perpendicular to the molded surface. The values of energy absorbed by each specimen are given in table V together with the averages and the average deviation from the mean. Very little difference was observed between values obtained from the two different sheets. It is perhaps worthy of note that the differences between tests with notch perpendicular and notch parallel to the original surface are not consistent between the Charpy and Izod tests, indicating that the impact strength of the material was substantially independent of the position of the notch.

The average of all the Izod tests was 20.0 inch-pounds for the $\frac{1}{2}$-inch specimen, which was about 20 percent greater than the average of all Charpy tests. The average of all Charpy tests was 15.6 inch-pounds. The difference is perhaps due to the fact that in the Izod tests an appreciable amount of energy was absorbed in a scraping action between the striking edge of the tup and the specimen.

8. Creep Tests

Creep tests in tension were performed at stresses ranging from 1400 to 3700 pounds per square inch, using apparatus as shown in figures 7 and 8. Strain readings were taken at intervals of time over a period of as much as 8000 hours for some of the tests, and shorter periods for other tests. The results of the creep tests are shown in figures 23 and 24. In figure 23 creep in percent was plotted against the elapsed time in hours for a total of 3000 hours. A similar diagram for a time of 8000 hours is shown in figure 24. Creep, as usually defined, is the total change in length (including elastic stretch) between gage points located in the cylindrical portion of the specimen expressed as a percentage of the original distance between gage points.

A rapid rate of creep was observed during the first interval of time. During this period the rate of creep decreased and was followed by a long period of creep at a relatively uniform rate. This latter period is referred to here as the "first stage" of creep. The initial portion of decreasing rate of creep is referred to as the "first transition region." The scatter in the plotted points for some of the tests is probably due in part to the difficulty of measuring changes in length of such small magnitudes and in part to the effect of intermittent vibrations of the building or to occasional short-time interruption of the air-conditioning equipment. It was observed that the rate of creep after about 3000 hours decreased appreciably, so that the curves approached nearly to a horizontal line for all values of stress (fig. 24). This tendency was similar to that observed for relatively high stresses in the case of cellulose acetate (reference 7).

It was found that the creep at any time within the limits of the test and at a given stress could be approximately represented by a straight line of slope R and intercept e_0; thus, $e = e_0 + Rt$ where e_0 is the "initial" creep, R the rate of creep, and e the total creep at time t. The values of e_0 and R were obtained by drawing a straight line through the points representing the first stage of creep (fig. 23). The slope of this line was the rate of creep R during the first stage of creep, and the intercept of this line with the zero-time axis was the initial creep e_0. When the rate of creep was plotted as a function of the stress on a log-log diagram (fig. 25), it was found that the data thus plotted could be represented reasonably well by a straight line, so that the rate of creep could be expressed as a power function of the stress. Similarly, the log-log plot of stress against initial creep was nearly a straight line, so that the initial creep could also be expressed as a power function of the stress (fig. 25).

Thus it was possible to express creep at any time t and any stress σ, by the following relationship: (The numbers "4600" and "9500" are dimensional coefficients.)

$$e = \left(\frac{\sigma}{4600}\right)^{3/2} + \left(\frac{\sigma}{9500}\right)^{5/2} t$$

This equation is, of course, an approximation to the creep curve. It represents a family of straight lines having slopes equal to the slope of the creep curve in the first stage and passing through the creep curves in the first stage. The family of straight lines represented by the above equation is shown, for the values of stress used in the tests, as dash lines in figure 23. Exact agreement between these lines and the plotted data is not to be expected because of the scatter of the plotted points shown in figure 25. The dash lines shown in figure 23 obviously will not accurately represent creep in the first transition region nor during the "second stage" of creep. In these cases, however, the actual creep is less than that predicted by the equation, so that use of the equation would be on the safe side.

9. Fracture Under Long-Continued Constant Load

These tests were supplemental to creep tests. The time required to cause fracture under a constant tension load is shown in figure 26, in which the tension stress is plotted against time for fracture on a log-log scale. It was observed that above a stress of about 3200 pounds per square inch, fracture almost always occurred within a relatively short time (less than 100 hr), but below this stress no fracture occurred in less than 2000 hours. Figure 26 indicates that the time required for fracture to take place under a constant stress increases with decrease in stress and that in the neighborhood of 3200 pounds per square inch a relatively small change in stress may make a very large change in time for the fracture to take place.

10. Fatigue Tests

(a) The effect of range of stress on the fatigue strength in bending.- In this paper "range of stress" is defined in terms of two quantities, the mean stress and the alternating stress of the stress cycle; that is, the cycle of stress is resolved into two components: a constant or mean value of bending stress σ_m and an alternating stress σ_a, which is superimposed on the mean stress. When the mean stress is zero, the maximum alternating stress which will cause fracture after a given number of cycles of stress is called the fatigue strength at the given number of cycles. When the mean stress is not zero, the corresponding value of maximum alternating stress σ_a which will produce fracture after a given number of cycles of stress is defined as the fatigue strength for that value of mean stress and the given number of cycles of stress.

Fatigue tests of phenolic molding material were run on specimens as shown in figure 3a for four different ranges of stress. The σ - N diagram for the four different values of mean stress is shown in figure 27. In this figure the alternating component of stress was plotted against the number of cycles for fracture on a semilog diagram. An appreciable scatter of data was observed in these tests, so that a definite σ - N curve could not be drawn. For purposes of analysis, a straight line was drawn through the plotted points representing the trend of the curve. The greatest emphasis was placed on tests at large numbers of cycles in drawing this line. In order better to illustrate the effect on the fatigue strength of a change in the mean stress, the fatigue strength at 100,000,000 cycles was plotted against the mean stress of the cycles in figure 28. It was observed that the fatigue strength decreased with increasing mean stress from 3130 pounds per square inch at zero mean stress to 1610 pounds per square inch at a mean stress of 7000 pounds per square inch. (See table VI.) (The speed of testing used in all of these tests was 1720 cpm.)

During the conduct of the tests in which the mean stress was not zero, it was observed that the mean stress continuously decreased even though the deflections of the specimen were maintained the same. This decrease in mean stress (relaxation) was the result of creep of the material. In order to show the effect of relaxation on the alternating-stress against mean-stress diagram (fig. 28), the fatigue strength was plotted against the value of mean stress which obtained at 100,000,000 cycles. These data are shown by the open circles in figure 28. The average value of the "static" ultimate strength in flexure (modulus of rupture), obtained in tests reported above, was plotted on the diagram in figure 28. A straight line drawn between the fatigue strength at zero mean stress and the "static" bending strength represents the "theoretical" effect of mean stress (reference 11). It was observed that the data adjusted to the mean stress at 100,000,000 cycles fell very nearly on this straight line.

(b) Relaxation during fatigue tests.- The effect of relaxation was further studied by means of a relaxation test conducted under static conditions in which the initial value of the bending stress was 7000 pounds per square inch. This test was conducted by using a dynamometer and specimen exactly the same as that used in the fatigue test. A deflection was given to the specimen sufficient to produce 7000 pounds per square inch. Readings of stress were recorded at intervals of time for a period of 800 hours. These data were plotted in figure 29 in which stress was plotted against time in hours. The value of the mean stress which obtained during fatigue tests at three different ranges of stress is also plotted in figure 29. These data were taken from the specimen which failed most nearly at 100,000,000 cycles. It was observed that relaxation of stress was quite rapid during the first 100 hours. Thereafter the stress decreased nearly as a linear function of time. It was also observed that the rate of decrease of mean stress increased with the value of the mean stress.

(c) Fatigue strength in torsion and bending.- In order to determine the behavior of the molding material in fatigue under a different state of stress, the material was tested in torsional fatigue, using the machine shown in figure 10. The σ - N diagram for fatigue tests in torsion of round specimens (fig. 3b) is shown in figure 30. For comparison, a fatigue curve was also obtained in bending with the same circular cross-sectional specimen as used in torsion and with specimens taken from the same sheet. The $\sigma - N$ diagram for these tests is also shown in figure 30. The fatigue strength for torsion tests was found to be 1800-pounds-per-square-inch shearing stress. (See table VI.) The corresponding fatigue strength in bending was found to be 3820-pounds-per-square-inch tensile stress. The fracture of the torsion specimen progressed along a 45° helix, indicating that the crack progressed along a plane of maximum tensile stress. (See fig. 33h.) However, the tensile stress in the torsion specimen was the same as the shearing stress, namely, 1800 pounds per square inch at the fatigue strength, whereas the tensile fatigue strength in bending was found to be 3820 pounds per square inch. This indicates that the start of the fatigue crack probably was the result of a shearing stress rather than a tension stress, because the maximum shearing stress in the bending specimen was one-half the maximum tensile stress, or 1910 pounds per square inch, which compares favorably with the shearing fatigue strength found in the torsion test, 1800 pounds per square inch. Thus it would appear that the failure is governed by the shearing stress rather than by the tension stress.

(d) The effect of speed of testing on the fatigue strength.- The effect of speed of testing on the fatigue strength of the phenolic molding material was studied by use of rotating-cantilever-beam machines, as shown in figure 11 (specimen, fig. 3c). These machines were provided with a V-belt drive, so that different speeds could be obtained. The $\sigma - N$ diagrams obtained from tests at three different speeds - 1720, 4200, 6150 cycles per minute - are shown in figure 31. The effect of speed of testing was found by plotting the fatigue strength at 100,000,000 cycles against the speed in cycles per minute, as shown in figure 32. It was found that the fatigue strength decreased as the speed was increased over the range of speed studied. The fatigue strength at a speed of 1720 cycles per minute, as obtained in these tests, was 2630 pounds per square inch. (See table VI.) It may be that the effect of speed on the fatigue strength was in part due to rise in temperature of the specimen due to the internal friction in the material. Since the specimen was rotating during the tests it was not found possible to measure the temperature; however, observations indicated that the temperature rise was not excessive.

(e) The effect of a notch on the fatigue strength.- The effect of a notch of shape as shown in figure 3d was obtained by tests on a rotating-beam machine at a speed of

6150 cycles per minute. The σ - N diagram for this test is shown in figure 31. The fatigue strength at 100,000,000 cycles was found to be 2300 pounds per square inch. Comparing this with the test of smooth specimens at the same speed, it was found that the fatigue strength was about 15 percent higher for the notched test than for the unnotched test. (See table VI.) It is difficult to explain an increase in fatigue strength as a result of notching the specimen. It may be, however, that this apparent increase is due largely to variations in the material between sheets or scatter in the data. However, the conclusion that this material is relatively insensitive to notches seems justified. This is in opposition to results of tests of cellulose acetate (reference 6), inasmuch as the fatigue strength of a notched specimen for cellulose acetate was found to be about one-half the fatigue strength of the unnotched specimen.

(f) The effect of type of test and shape of specimen.- Comparison of the fatigue strength obtained at a speed of 1720 cycles per minute and a mean stress of zero, but different types of machine and different shapes of specimen, showed the following results. The fatigue strength of a square specimen in the bending machine was 3130 pounds per square inch, while for a circular cross-sectional specimen the fatigue strength was 3820 pounds per square inch - an increase of about 21 percent. A circular cross-sectional specimen of the same shape but tested in a rotating-beam testing machine was found to give a fatigue strength of 2630 pounds per square inch, or a decrease of 31 percent of the results obtained in the circular bending specimen. These differences may be due in part to variations in the material, particularly in the case of the latter since the rotating-beam specimens were obtained from material 0.5 inch thick and the bending specimens from materials 0.3 inch thick. Difference in surface finish may also contribute to the variation between results obtained on different machines. The original molded surface remained on all square cross-sectional specimens, whereas the surface of circular cross-sectional specimens was machined and then sanded. A similar increase of fatigue strength of circular as compared to square specimens was found for cellulose acetate as well as for the phenolic molding material. (See reference 8.)

Fractured fatigue specimens of all types used are shown in figures 33f...k.

VI. CONCLUSIONS

The following conclusions may be drawn from the above tests of macerated phenolic molding material performed at a constant temperature of 77° F and relative humidity of 50 percent.

1. Static short-time tension and compression tests performed at the same rate of strain indicate about equal values of yield strength in tension and compression - 4010 and 4120 pounds per square inch, respectively (at 0.05 percent offset). (See tables I, II, III.)

2. The ultimate strength in compression is, however, about four times the ultimate strength in tension - 18,960 and 4550 pounds per square inch, respectively.

3. The moduli of elasticity are nearly equal in tension and compression - 981,000 and 886,000 pounds per square inch, respectively.

4. Torsion tests at a rate of strain corresponding to that used for the tension and compression tests showed a yield strength (at 0.05 percent offset) about 60 percent of the corresponding value in tension and compression - 2550 pounds per square inch (table IV).

5. The modulus of elasticity in shear was about one-fourth of that in tension and compression - 234,000 pounds per square inch in one group of specimens; 290,000 pounds per square inch in another group.

6. Torsion tests at different rates of strain showed that the shearing yield strength increased with increasing rate of strain up to a rate of strain of about 0.01 inch per inch per minute. (See fig. 19.)

7. It was found that a time of about 40 days was required for the specific weight to approach equilibrium in an atmosphere of constant temperature and humidity (fig. 20). The change in specific weight was attributed to change in moisture content.

8. The compressive strength of the material changed during the time that the moisture content was not in equilibrium with the humidity of the atmosphere. The strength

increased during the time that the moisture content of the material was greater than that required for equilibrium with the atmosphere, and decreased when the moisture content was less than that required for equilibrium with the atmosphere (fig. 21).

9. The modulus of rupture in flexure was found to be 8000 pounds per square inch.

10. The average energy absorbed in breaking a $\frac{1}{2}$- by $\frac{1}{2}$-inch Izod impact specimen was 20 inch-pounds; whereas, the average energy absorbed by a $\frac{1}{2}$- by $\frac{1}{2}$-inch Charpy specimen was 15.6 inch-pounds. There was no appreciable difference in impact strength of specimens with notch cut parallel to the surface of the sheet and specimens with notch cut perpendicular to this surface (table V).

11. Creep tests at several different stresses showed that the amount of creep and rate of creep are increased by an increase in stress. It was also observed that the largest proportion of the creep recorded occurred during the early part of the test (fig. 23).

12. It was observed that the creep against time curve approached a horizontal line after a time of about 3000 hours for all values of stress (fig. 24).

13. It was found that the creep occurring during a time of about 3000 hours could be represented approximately by the following equation:

$$e = \left(\frac{\sigma}{4600}\right)^{3/2} + \left(\frac{\sigma}{9500}\right)^{5/2} t$$

14. Tension tests conducted at a constant load for long periods of time showed a critical stress of 3200 pounds per square inch, above which fracture occurred within less than 100 hours, and below which fracture did not occur for a long period of time.

15. The fatigue strength for completely reversed bending stress was found to be 3130 pounds per square inch at 100,000,000 cycles.

16. Tests at other ranges of stress showed that the fatigue strength decreased with increasing mean stress from 3130 pounds per square inch at zero mean stress to

1610 pounds per square inch at a mean stress of 7000 pounds per square inch (table VI).

17. Relaxation of stress occurred during fatigue tests in which the range of stress was not zero. The relaxation rate was found to be affected not only by the value of the mean stress but also by the presence of an alternating stress (fig. 29).

18. The fatigue strength in torsion was 1800-pounds-per-square-inch shearing stress at 100,000,000 cycles (table VI).

19. The fatigue strength of a circular cross-sectional specimen in bending was found to be 3820 pounds per square inch, which was about twice the fatigue strength of identical specimens in torsion. This indicates that shearing stress may be the governing stress which initiates the fatigue crack (table VI).

20. Rotating-beam fatigue tests at different speeds of testing showed that the fatigue strength decreased as the speed of testing increased (fig. 32).

21. Tests of notched rotating-beam specimens indicated very little notch sensitivity. There was some indication that the presence of a notch increased the fatigue strength (table VI).

22. Differences of 20 to 30 percent in fatigue strength were found for different shapes of specimens and different types of testing machines (table VI).

VII. APPENDIX

Definition of Terms

1. <u>Modulus of elasticity</u>. In this report modulus of elasticity is understood to refer to the tangent modulus at the initial portion of the stress-strain curve; that is, the modulus was obtained by measuring the slope of a line drawn tangent to the curve through the lower portion of the curve. It is important to note that friction lag or backlash in the strain-measuring instrument may result in some irregularity in position of the first two or three readings and, because of this lag, the stress-strain curve will not necessarily pass through the origin of coordinates.

2. Yield strength.- Yield strength is designated as the stress corresponding to an arbitrarily selected percent deviation from the straight-line portion of the curve (or "modulus line"). It is obtained from a plotted stress-strain curve by drawing a line parallel to the modulus line and at a distance from this line equal to the specified offset measured along the strain axis. The yield strength is the stress corresponding to the point of intersection of the stress-strain curve and the auxiliary line mentioned above.

3. Rate of strain.- The rate of strain as used in this report refers to the time rate of straining of the specimen in the elastic (or straight line) portion of the stress-strain curve. In the case of the tension and compression tests, the value of the rate of strain was obtained from the slope of a strain-time diagram plotted from data taken during the tests. In the case of the tension and compression tests, strain-time diagrams such as figures 13 and 15 are obtained. The rate of strain as interpreted for these diagrams was the slope of the curve at the portion just below the value of strain corresponding to the maximum strain for which stress was directly proportional to strain.

4. Modulus of rupture.- The modulus of rupture is a fictitious stress obtained, in the case of the torsion test, by substituting the maximum value of twisting moment into the equation $\tau = \frac{Tc}{J}$. The value of stress obtained does not represent the actual maximum stress in the material at the fracture, because the equation used is correct only when stress is directly proportional to the strain, which is not the case at rupture. Modulus of rupture in flexure is a fictitious stress obtained by substituting the maximum bending moment obtained in the flexure test into the equation $\sigma = \frac{Mc}{I}$. This does not represent the actual maximum stress at fracture because this equation also is correct only when stress is directly proportional to strain - a condition which is not true at rupture of a flexural member.

5. Creep.- Creep is designated as the total extension in a tension member which has occurred up to a given time as a result of a constant load; it is expressed in percent. It should be noticed that creep includes both the elastic stretch and the stretch which occurs progressively during the time of loading.

6. <u>Rate of creep</u>.- The rate of creep represents a time rate of extension of the tension member under a constant load. It is determined by measuring the slope of the straight-line portion of the creep-time curve. Note that the rate of creep times the time does not give the total creep.

7. <u>Fatigue strength</u>.- In this paper a cycle of repeated stress is resolved into two components - steady or mean stress upon which is superimposed an alternating stress. The maximum amplitude of an alternating stress cycle, expressed in pounds per square inch, which will not cause fracture of the material for a given number of cycles of alternating stress is called the fatigue strength. The number of cycles used in this paper was 100,000,000. If the stress cycle does not produce complete reversal of stress, the mean stress of the cycle must be stated when specifying the fatigue strength because in general the fatigue strength changes with different values of mean stress.

8. <u>Mean stress</u>.- The algebraic mean between the maximum and minimum stress produced in a material during an alternating cycle of stress. When used in conjunction with the fatigue strength, the term "mean stress" denotes the mean stress for which the stated fatigue strength was determined.

9. <u>Average deviation from the mean</u>.- This quantity is used as a measure of the scatter in experimental data and is obtained by forming the difference between each reading and the average of readings, then averaging these differences.

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TABLE I. STATIC TENSILE TESTS OF PHENOLIC MOLDING MATERIAL

(Specimen as Shown in Fig. 1a)

(Terms Defined in Appendix)

Specimen Number	Yield Strength 0.05 per cent offset, psi	Ultimate Strength psi	Ultimate Strain in. per in.	Modulus of Elasticity 1000 psi	Rate of Strain in. per in. per min.
25-B-5	3900	4790	0.00597	960	0.0015
25-B-6	3850	4320	0.00515	954	0.0015
25-B-10	3850	4550	0.00556	960	0.0015
26-B-11	4380	4430	0.00464	1050	0.0013
26-B-17	4050	4670	0.00577	980	0.0014
Average	4010	4550	0.00543	981	0.0014
Average Deviation from the Mean	170	140	0.00042	28	

Average No-Load Head Speed -- 0.040 in. per min.

TABLE II. STATIC COMPRESSION TESTS OF PHENOLIC MOLDING MATERIAL

(Specimen as Shown in Fig. 2a)

(Terms Defined in Appendix)

Specimen Number	Yield Strength		Ultimate Strength psi	Ultimate Strain in. per in.	Modulus of elasticity 1000 psi	Rate of Strain in./in./min.
	0.05% offset psi	0.2% offset psi				
203-A-10	3400	5500	12,700	----	970	0.0014
203-A-11	4700	6700	13,000	----	830	0.0015
203-A-9	4200	5900	13,200	0.0497	850	0.0016
203-A-12	4400	6400	13,800	0.0508	830	0.0015
203-A-13	3900	5800	13,200	0.0508	950	0.0016
Average	4120	6060	13,200	0.0504	886	0.0015
Average Deviation from the Mean	380	390	260	0.0005	59	

Average No - Load Head Speed -- 0.0105 in. per min.

TABLE III. STATIC COMPRESSION TESTS FOR ULTIMATE STRENGTH OF PHENOLIC MOLDING MATERIAL

(Specimen as shown in Fig. 2b)

Specimen Number	Ultimate Strength psi	Approximate Rate of Strain in./in./min.
203-A-5	18,560	0.0008
203-A-3	19,640	0.0008
203-A-2	19,640	0.0009
203-A-4	18,370	0.0015
203-A-6	18,610	0.0015
Average	18,960	
Average Deviation from the Mean	540	

TABLE IV. STATIC TORSION TESTS OF PHENOLIC MOLDING MATERIAL

(Specimen as Shown in Fig. 2e)

(Terms Defined in Appendix)

Specimen Number	Yield Strength 0.05°/o	Yield Strength 0.2%	Modulus of Rupture psi	Ultimate Strain in. per in.	Shearing Modulus, G, 1000 psi	Rate of Strain in./in./min. Tensile	Rate of Strain in./in./min. Shearing
305-T-11	2500	3180	3180	0.0155	232	.0012	.0050
305-T-13	2420	3130	3160	0.0158	236	.0012	.0050
305-T-15	2730	3560	3640	0.0173	235	.0014	.0058
Average	2550	3290	3330	0.0162	234		
Average Deviation from the Mean	120	180	210	0.0007	2		

Average No-Load Head Speed -- 0.024 revolutions per min.

TABLE V. IMPACT TESTS OF PHENOLIC MOLDING MATERIAL

(Specimens as shown in Fig. 1c and 1d)

(Terms defined in Appendix)

Type of Test	Sheet 311 Specimen	Sheet 311 Absorbed Energy in-lb	Sheet 314 Specimen	Sheet 314 Absorbed Energy in-lb	Average for both sheets in-lb
Izod--	I-4	22.0	I-4	18.0	
Notch Parallel to	I-3	20.0	I-3	21.3	
Original Surface	I-2	19.0	I-2	20.8	
	I-1	18.0	I-1	13.0	
Average		19.3		18.3	18.8
Average deviation from the Mean		1.2		2.8	
Izod--	I-8	21.5	I-8	21.5	
Notch Perpendicular	I-7	21.7	I-7	21.8	
to Original Surface	I-6	22.0	I-6	20.8	
	I-5	20.0	I-5	20.8	
Average		21.3		21.2	21.2
Average Deviation from the Mean		0.6		0.4	
		Average of All Izod Tests			20.0

Type of Test	Sheet 311 Specimen	Sheet 311 Absorbed Energy in-lb	Sheet 314 Specimen	Sheet 314 Absorbed Energy in-lb	Average for both sheets in-lb
Charpy--	IC-4	14.8	IC-4	21.3	
Notch Parallel to	IC-3	14.2	IC-3	17.8	
Original Surface	IC-2	18.7	IC-2	14.5	
	IC-1	19.9	IC-1	17.5	
Average		16.9		17.8	17.3
Average Deviation from the Mean		2.4		1.8	
Charpy--	IC-7	14.4	IC-7	13.4	
Notch Perpendicular	IC-6	11.8	IC-6	14.6	
to Original Surface	IC-5	13.5	IC-5	15.8	
Average		13.2		14.6	13.9
Average Deviation from the Mean		1.0		0.8	
		Average of All Charpy Tests			15.6

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Sheet Number	Specimen	Type of Test	Machine	Speed of Testing r p m.	Initial Mean Stress psi	Mean Stress At 100,000,000 cycles psi	Fatigue Strength at 100,000,000 cycles psi	
22,23, 29	Square Fig. 3a	"Range" of Stress in Bending	Bending Fig. 9	1720	0	0	3130	Tension Stress
31, 33, 34	"	"	"	1720	2000	1330	2580	"
33,34	"	"	"	1720	4000	2320	2280	"
34,35	"	"	"	1720	7000	3140	1610	"
47	Circular Fig. 3b	Bending of Circular Specimen	"	1720	0	--	3820	"
47	"	Torsion of Circular Specimen	Torsion Fig. 10	1720	0	--	1800	Shearing or Tension Stress
301, 302	Circular Fig. 3c	Effect of Speed	Rotating Beam Fig. 11	1720	0	--	2630	Tension Stress
302, 303	"	"	"	4200	0	--	2300	"
303	"	"	"	6150	0	--	2050	"
304	Notched Fig. 3d	Effect of Notch	"	6150	0	--	2300	"

TABLE VI. FATIGUE TESTS OF PHENOLIC MOLDING MATERIAL

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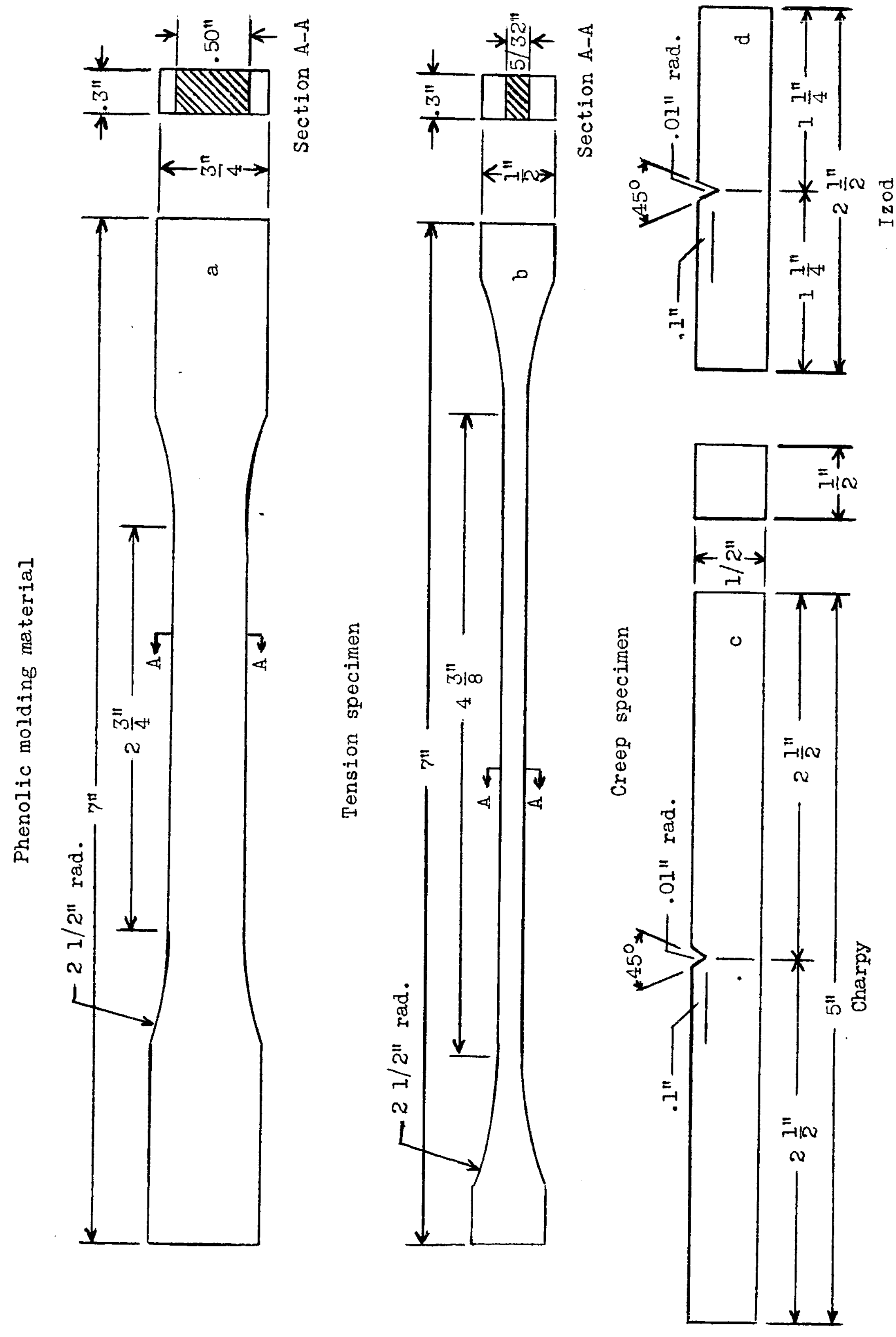


Impact specimens

Figure 1. - Specimens.

w-99

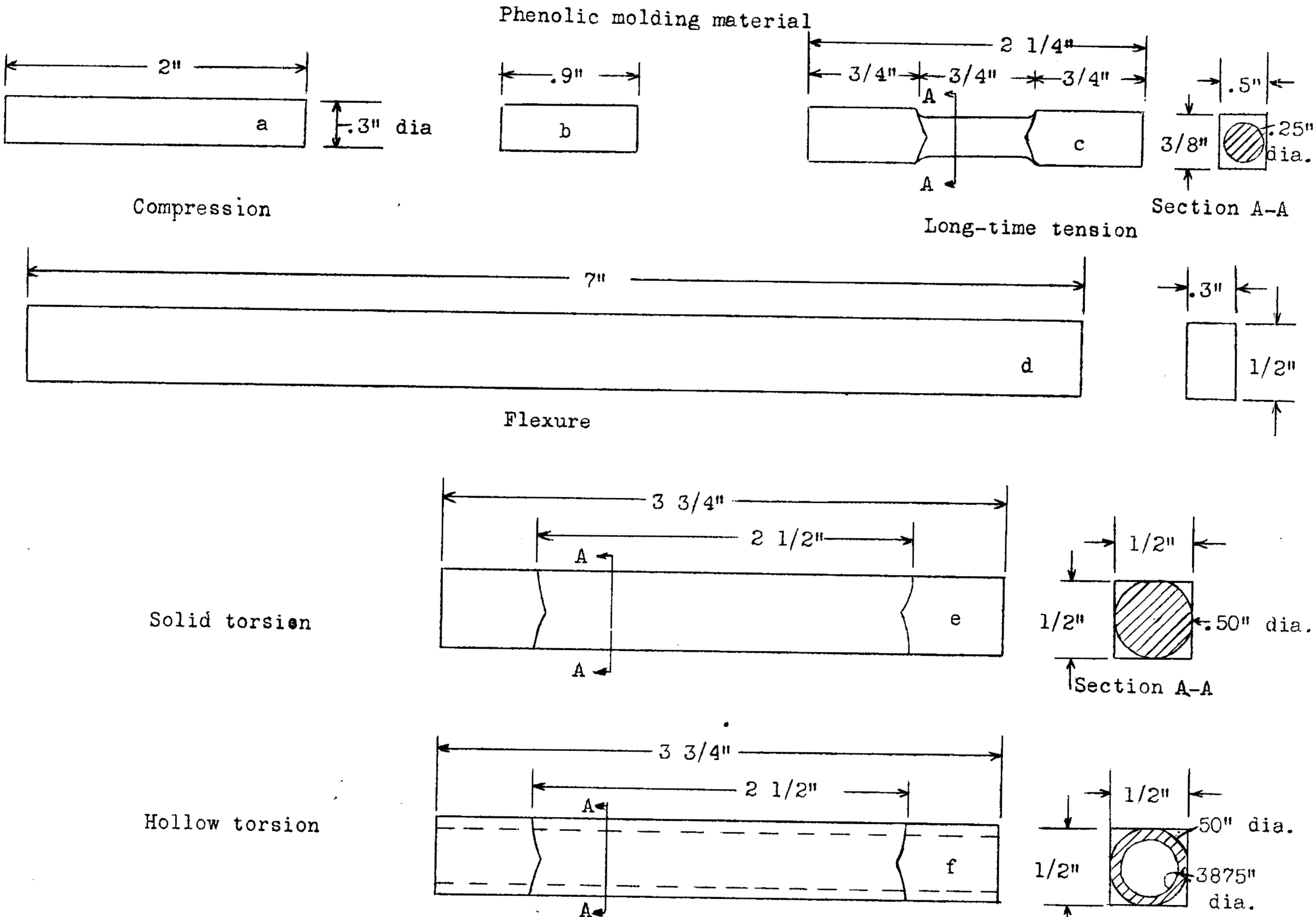
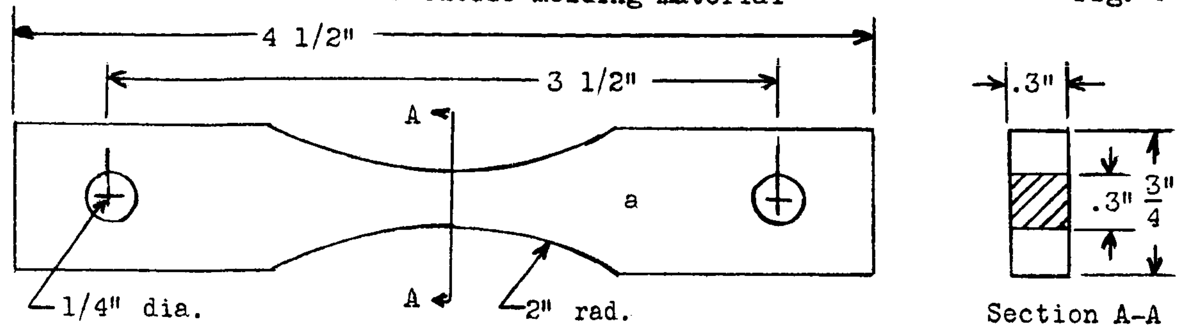
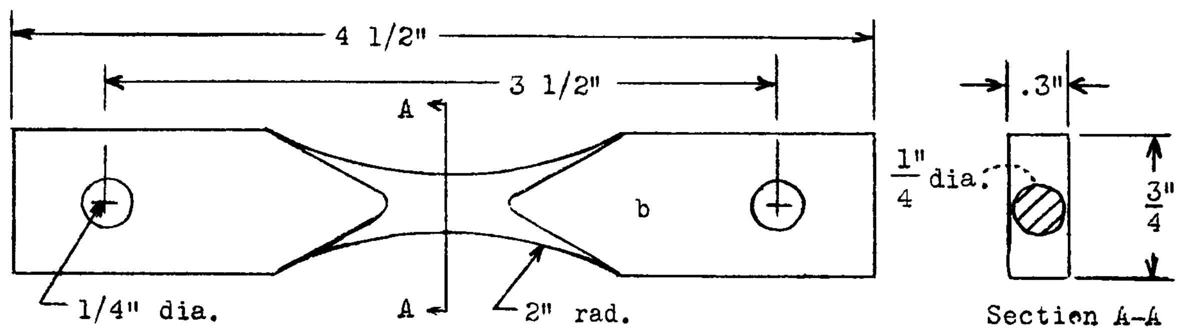


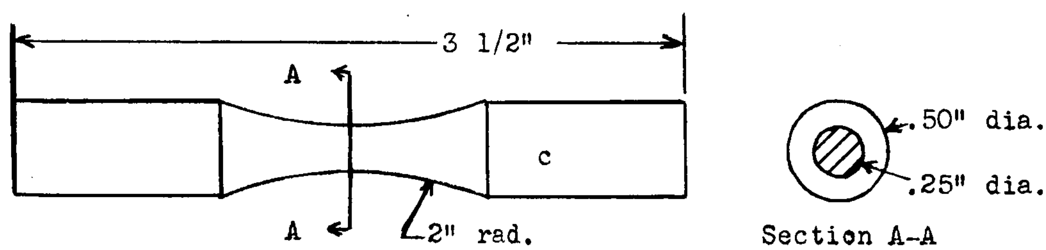
Figure 2.- "Static" specimens.



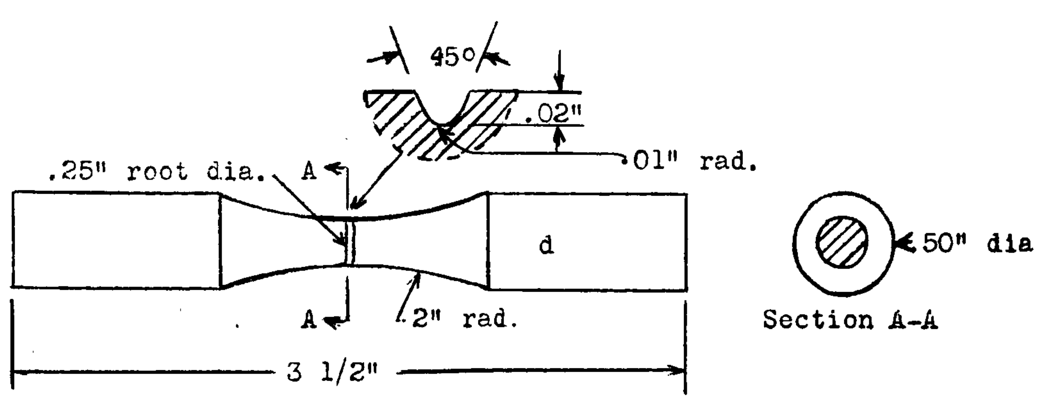
Square cross section bending



Circular cross section bending and torsion



Rotating beam



Notched rotating beam

Figure 3.- "Fatigue" specimens.

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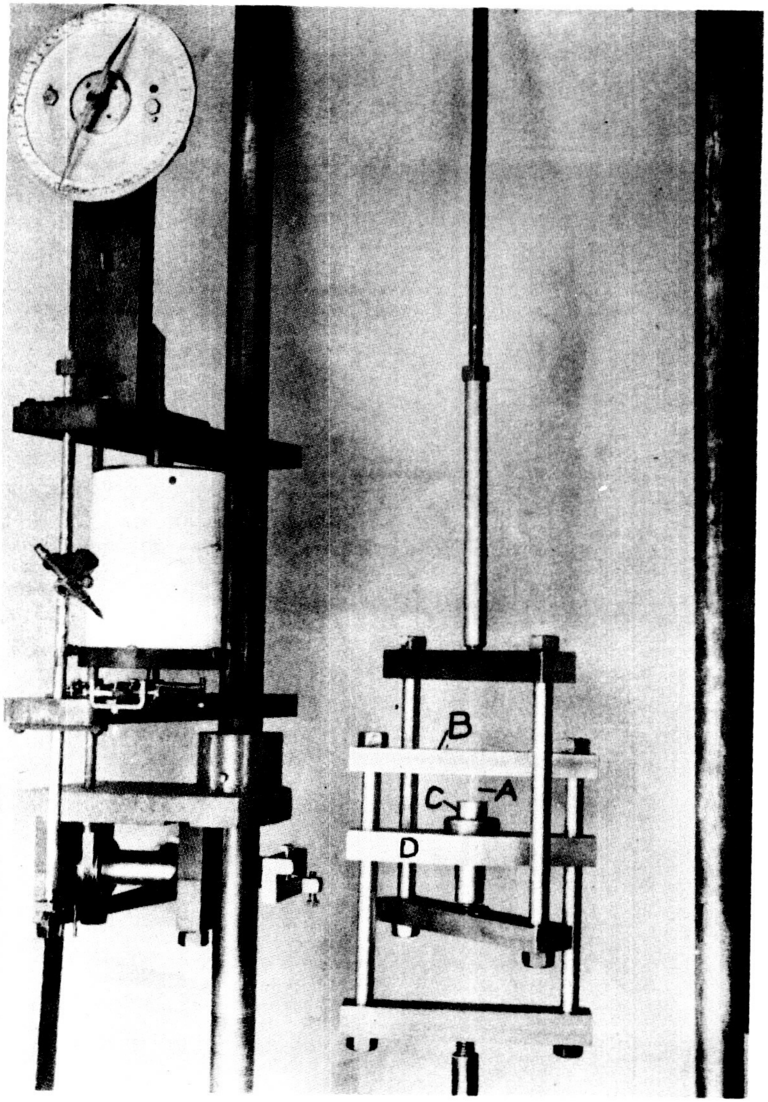

Figure 4.- Universal testing machine with compression tool.

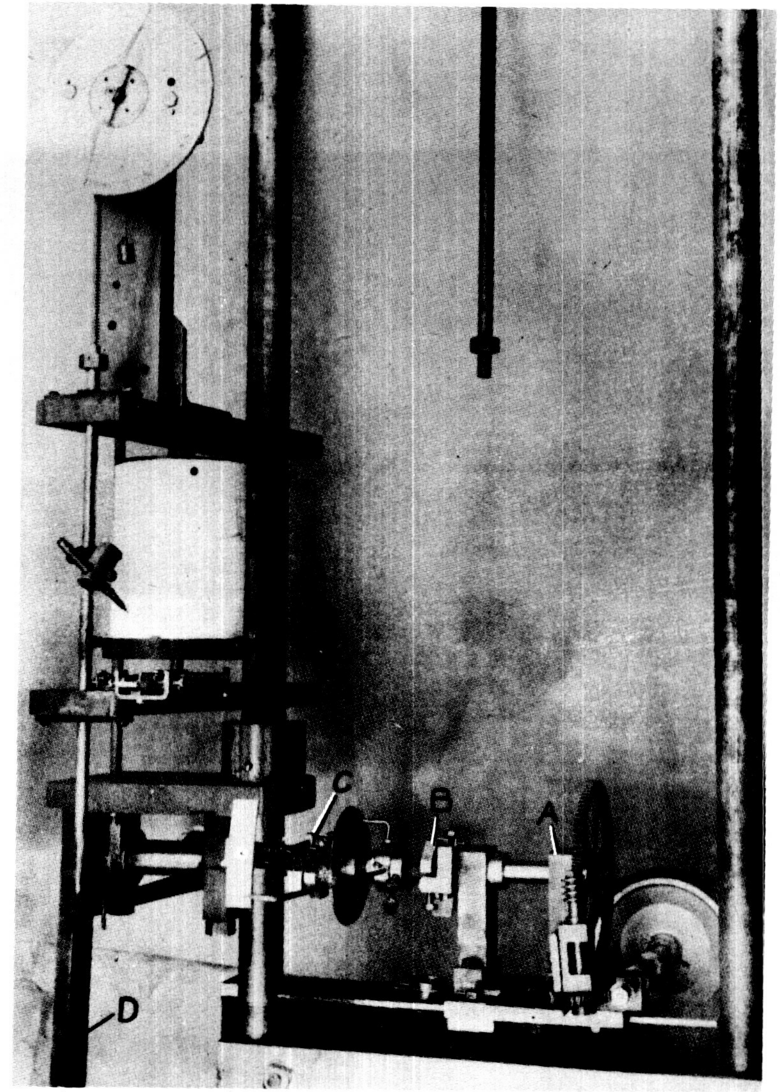

Figure 5.- Universal testing machine with torsion attachment and detrusion gage.

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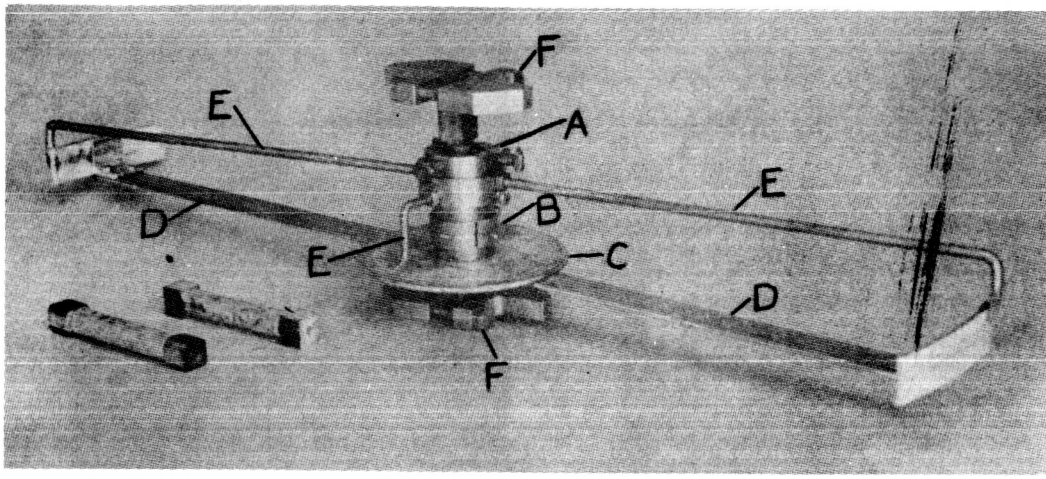

Figure 6.- Detrusion gage.

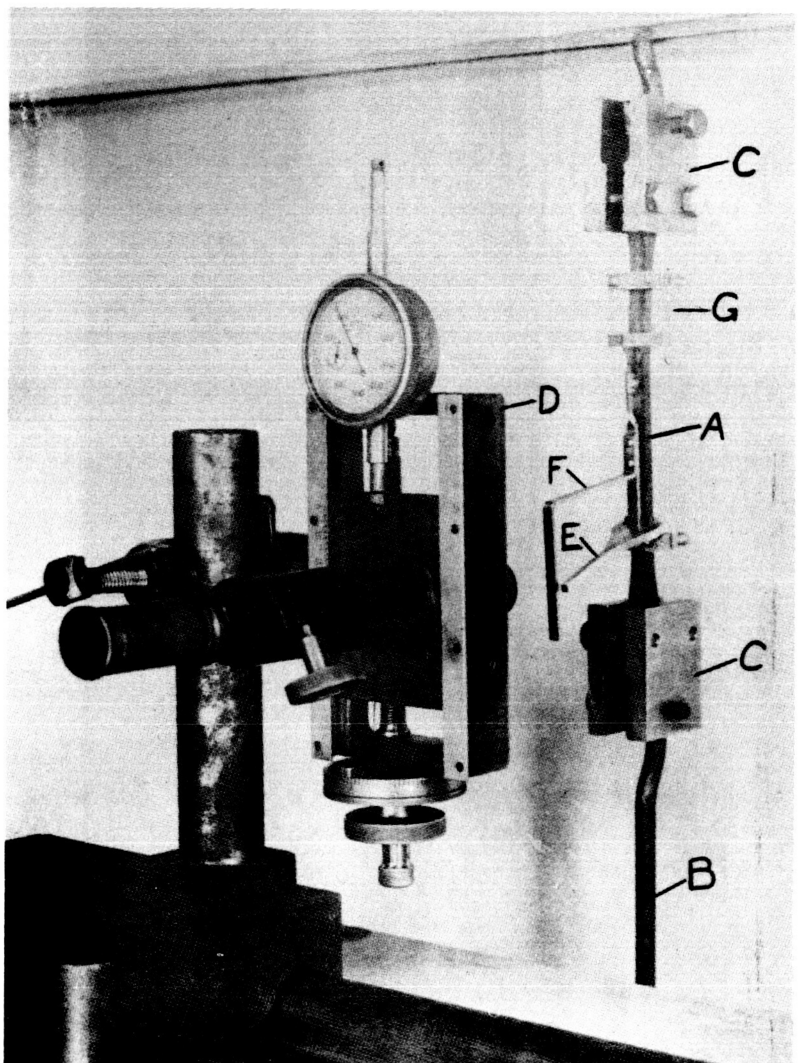

Figure 7.- Creep measuring apparatus.

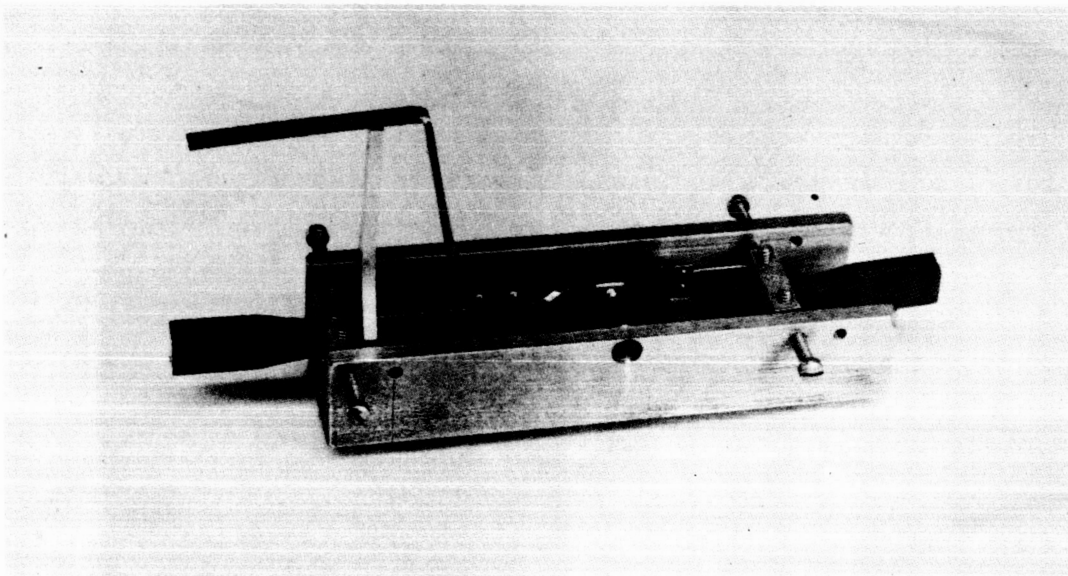

Figure 8.- Jig for assembling creep extensometer.

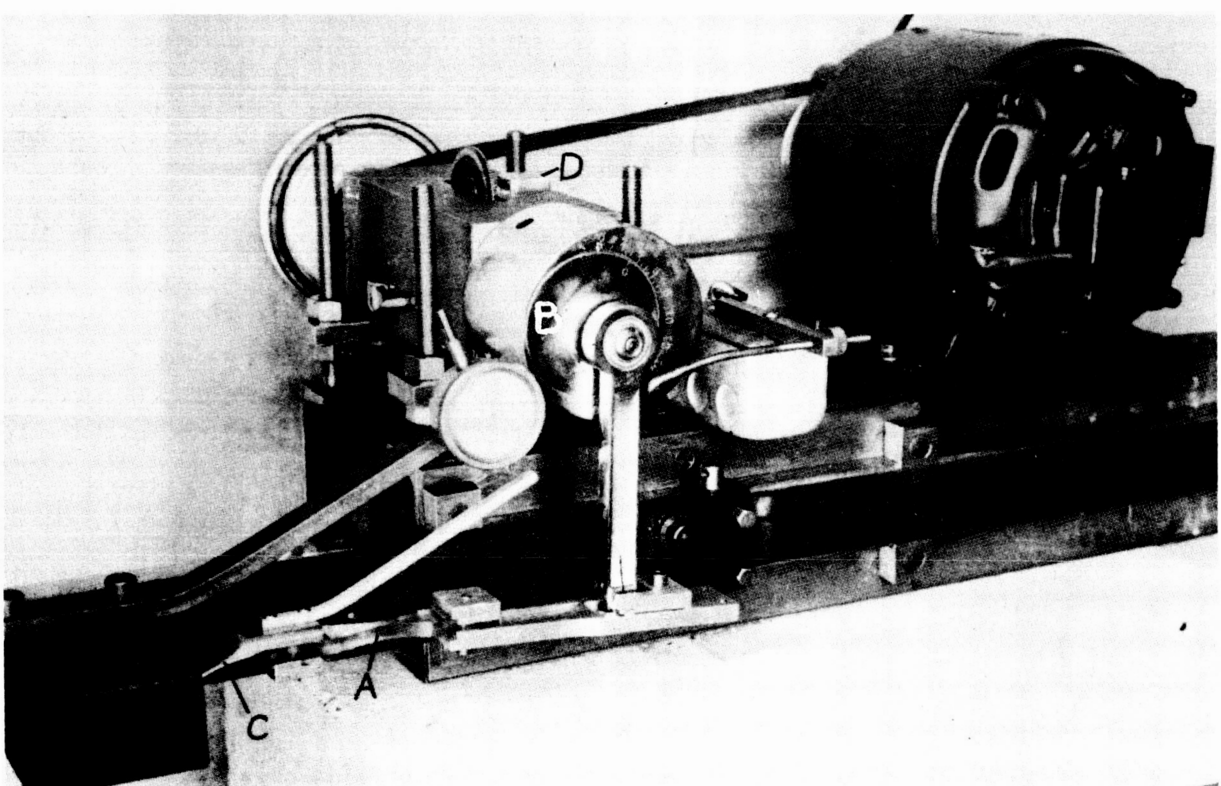

Figure 9.- Fixed-cantilever, constant-amplitude fatigue machine arranged for bending tests.

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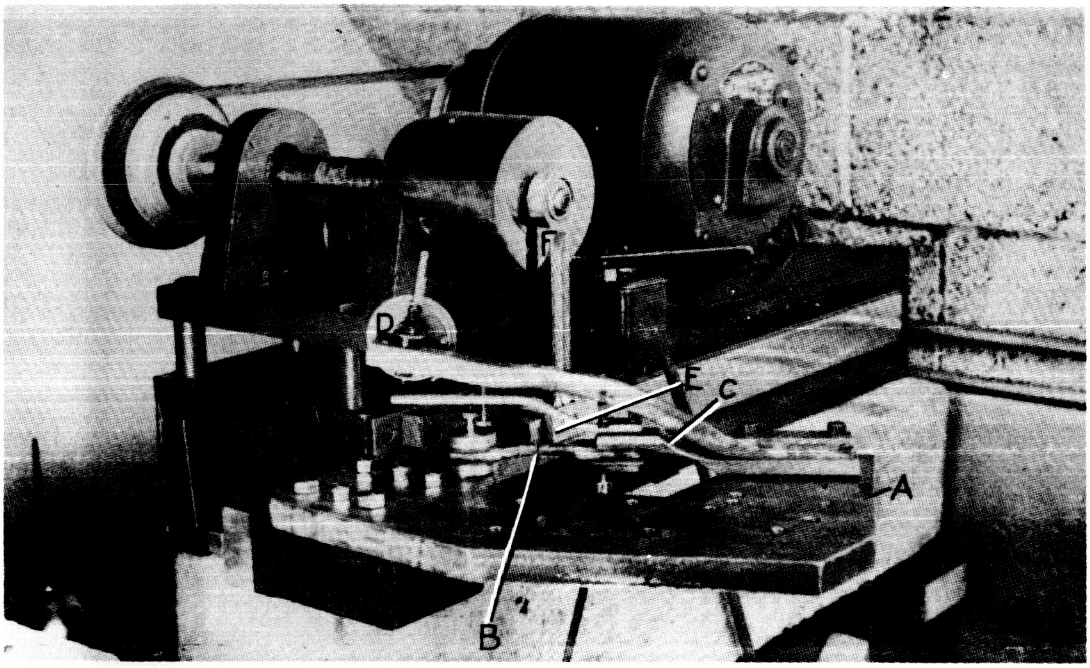

Figure 10.- Fixed-cantilever, constant-amplitude fatigue machine arranged for torsion tests.

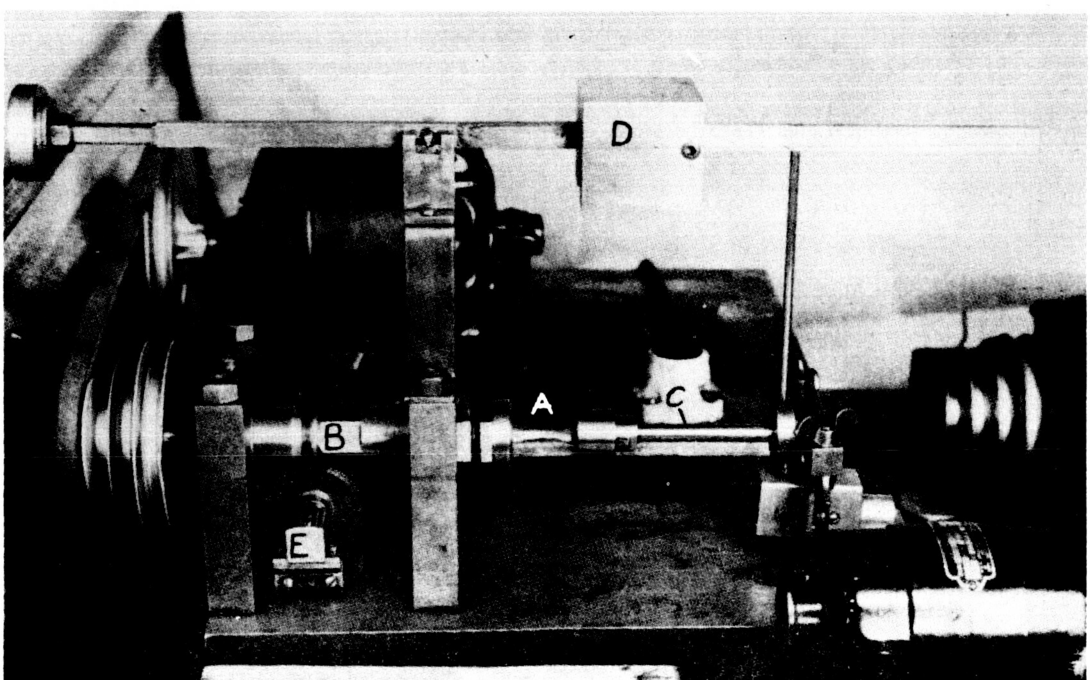

Figure 11.- Rotating-cantilever-beam fatigue machine.

W-99

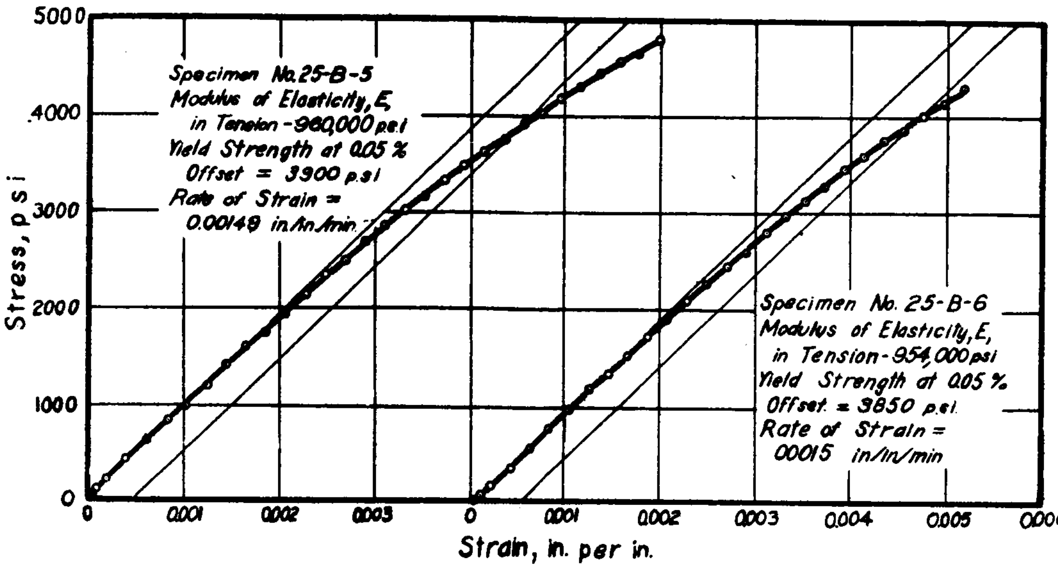

Fig. 12-A

Stress vs Strain in Tension

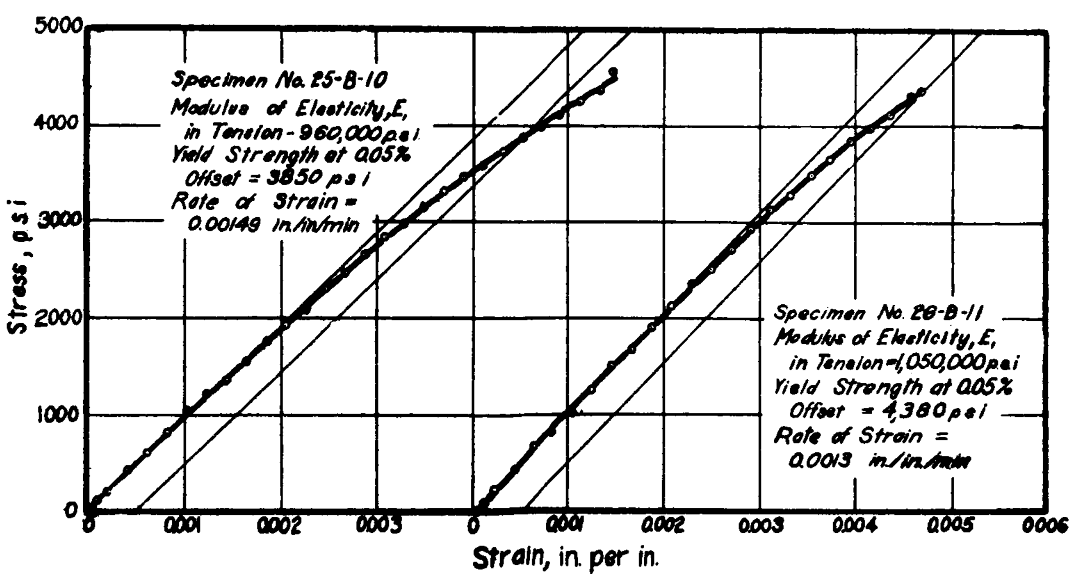

Fig. 12-B

Stress vs Strain in Tension

(1 block = 10 divisions on 1/20" engr. scale)

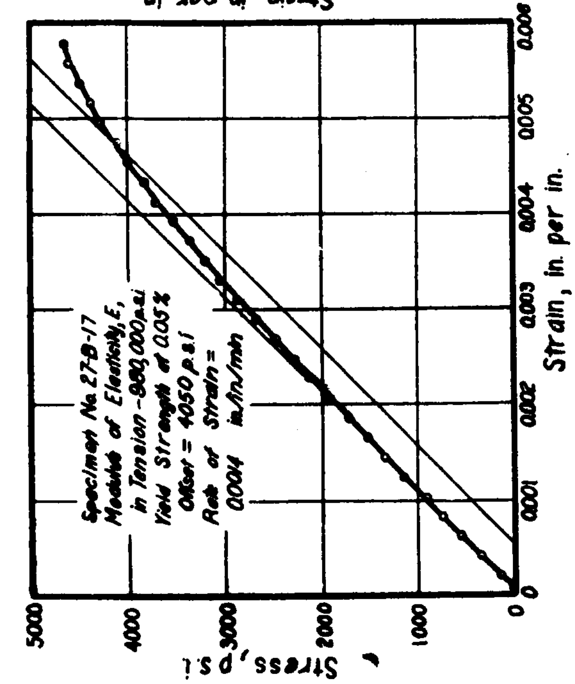

Fig.12-C

Stress vs Strain in Tension

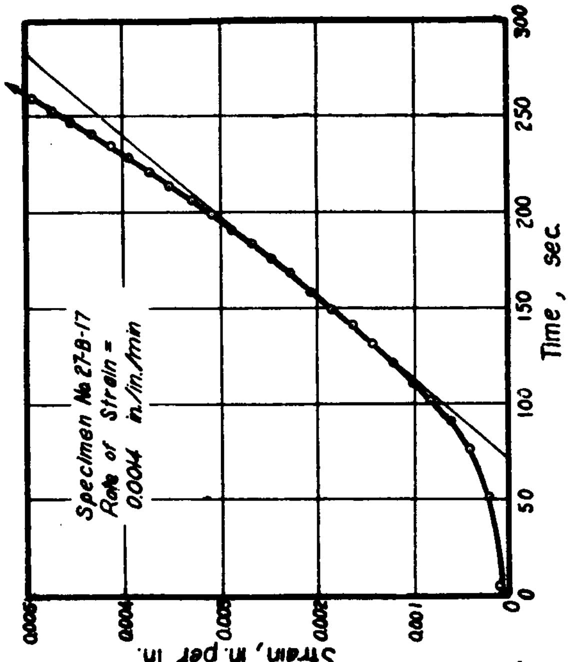

Fig.13

Strain vs Time in Tension

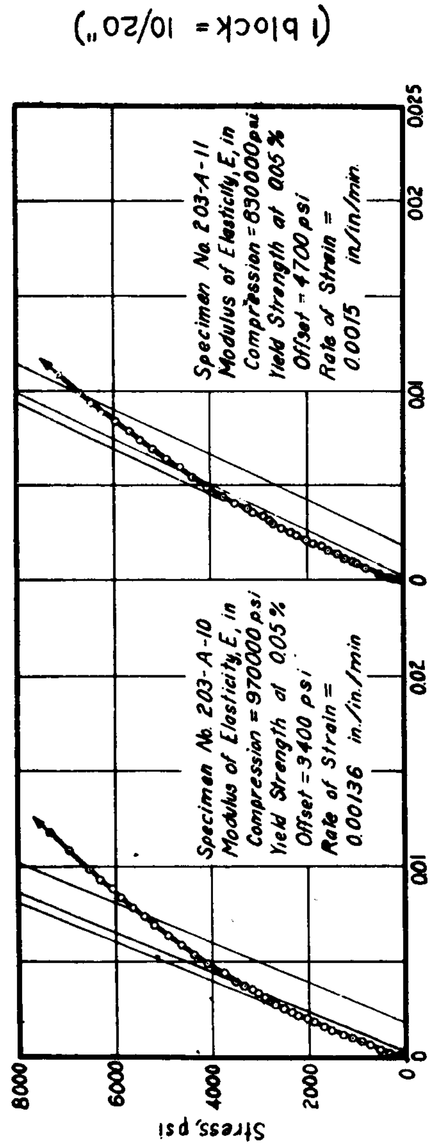

Fig14-A

Stress vs. Strain in Compression

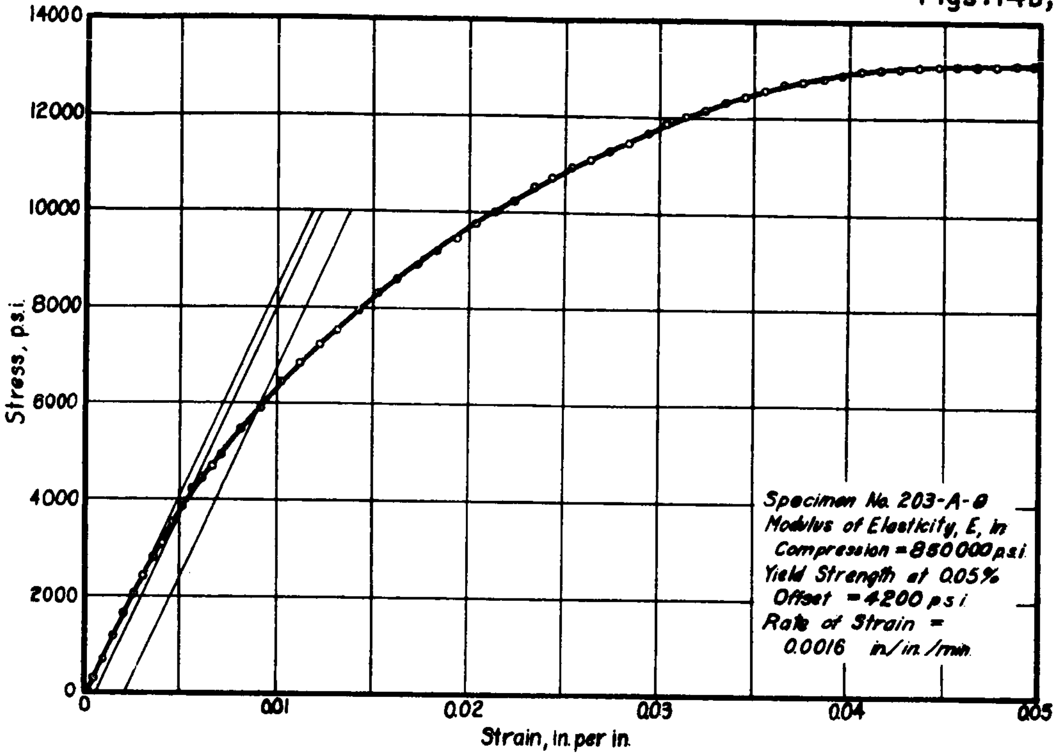

Fig. 14-B

Stress vs. Strain in Compression

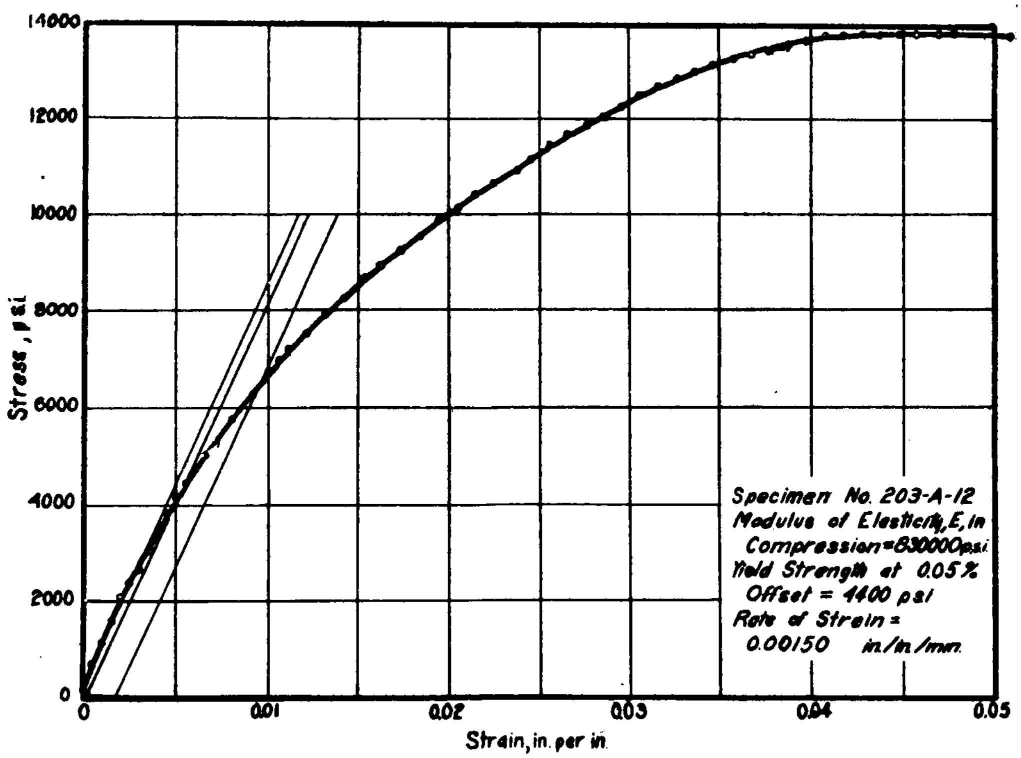

Fig. 14-C

Stress vs. Strain in Compression

(1 block = 10/20")

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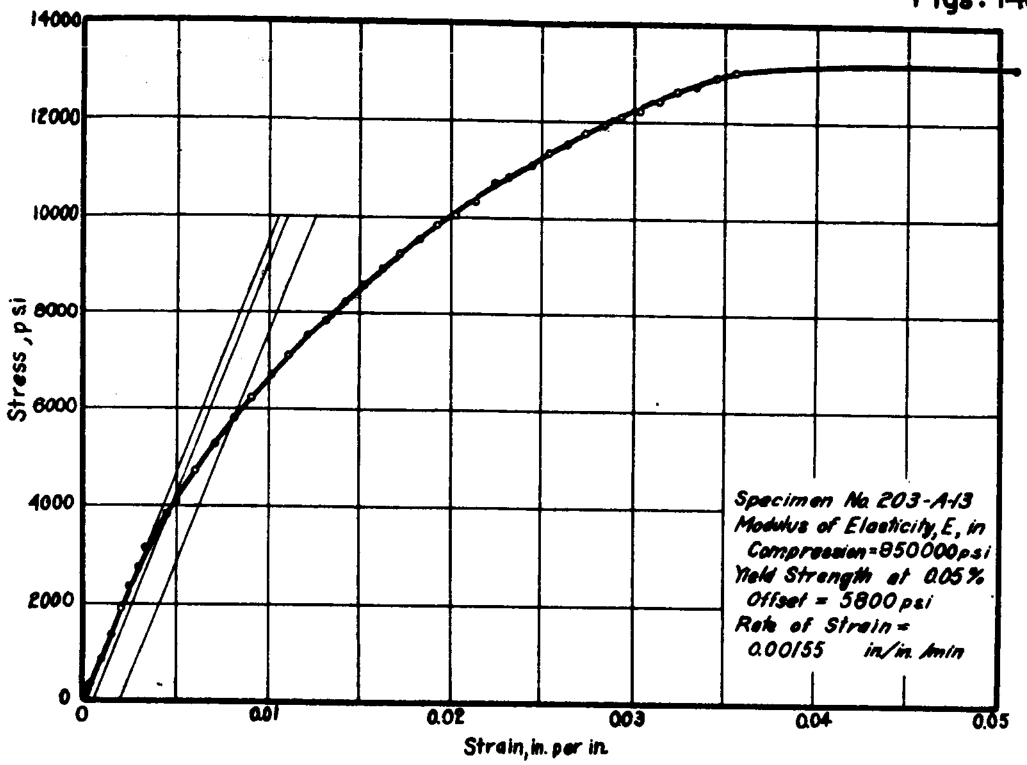

Fig. 14-D

Stress vs Strain in Compression

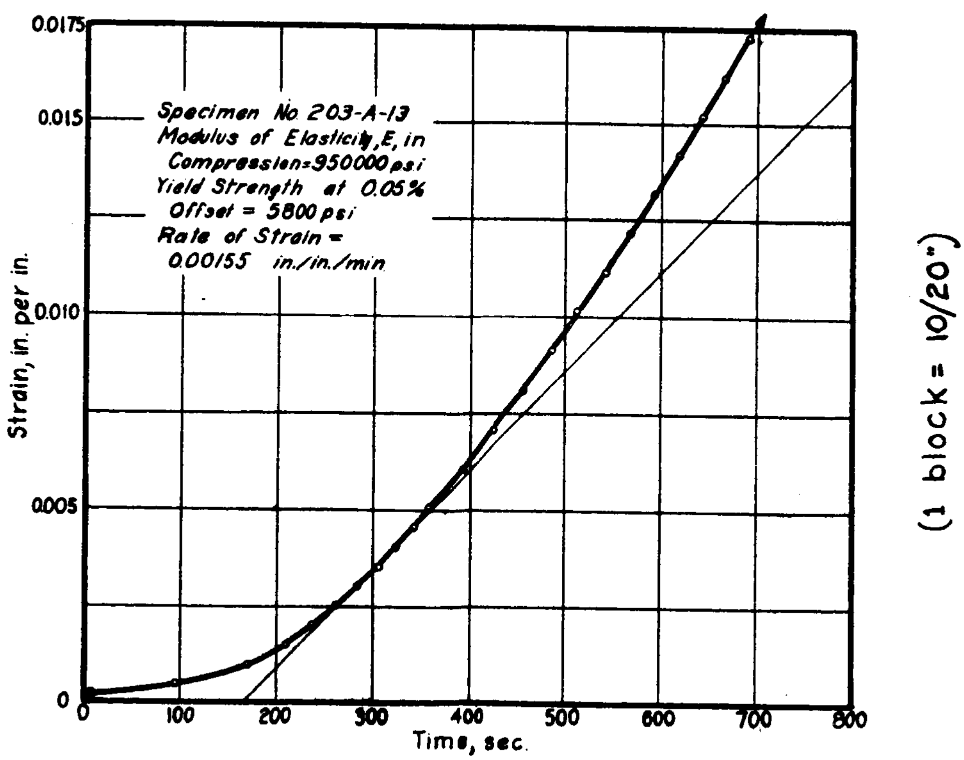

Fig. 15

Strain vs Time in Compression

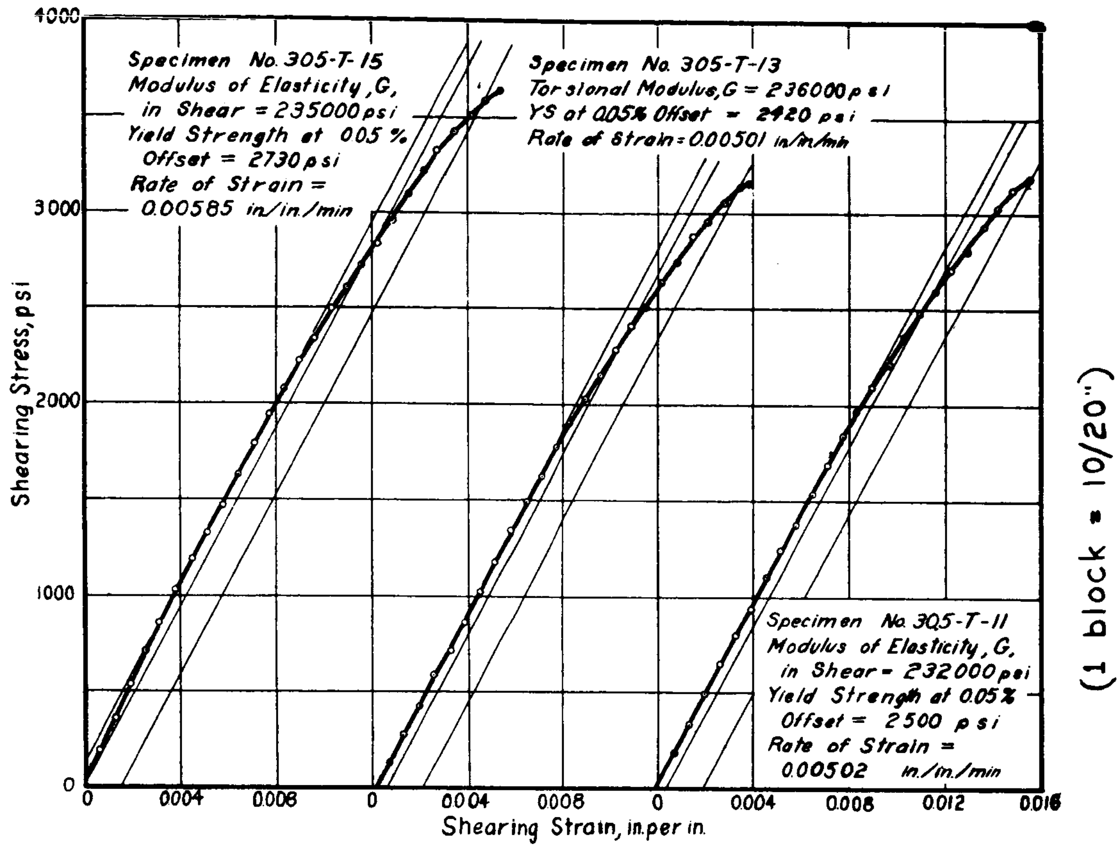

Fig. 16

Shearing Stress vs Strain in Torsion

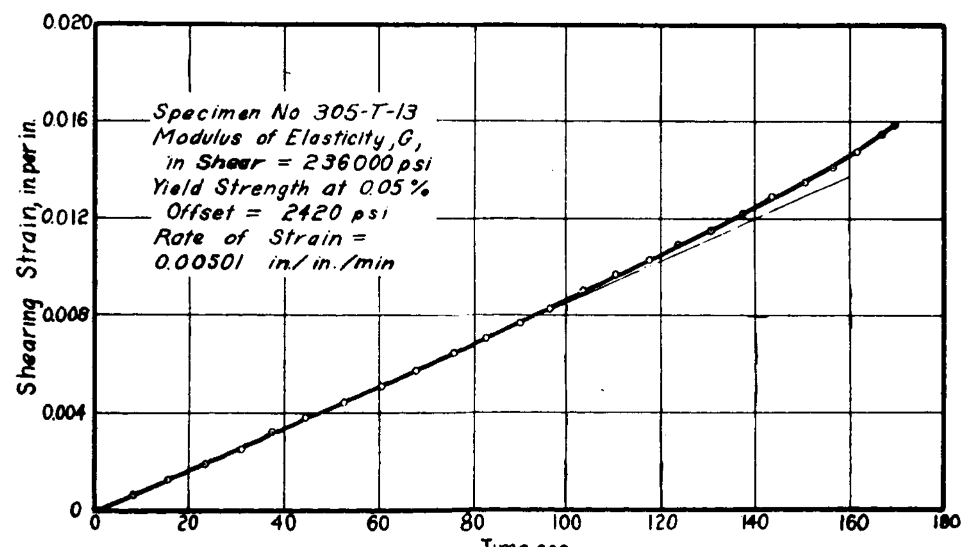

Fig. 17

Shearing Strain vs Time in Torsion

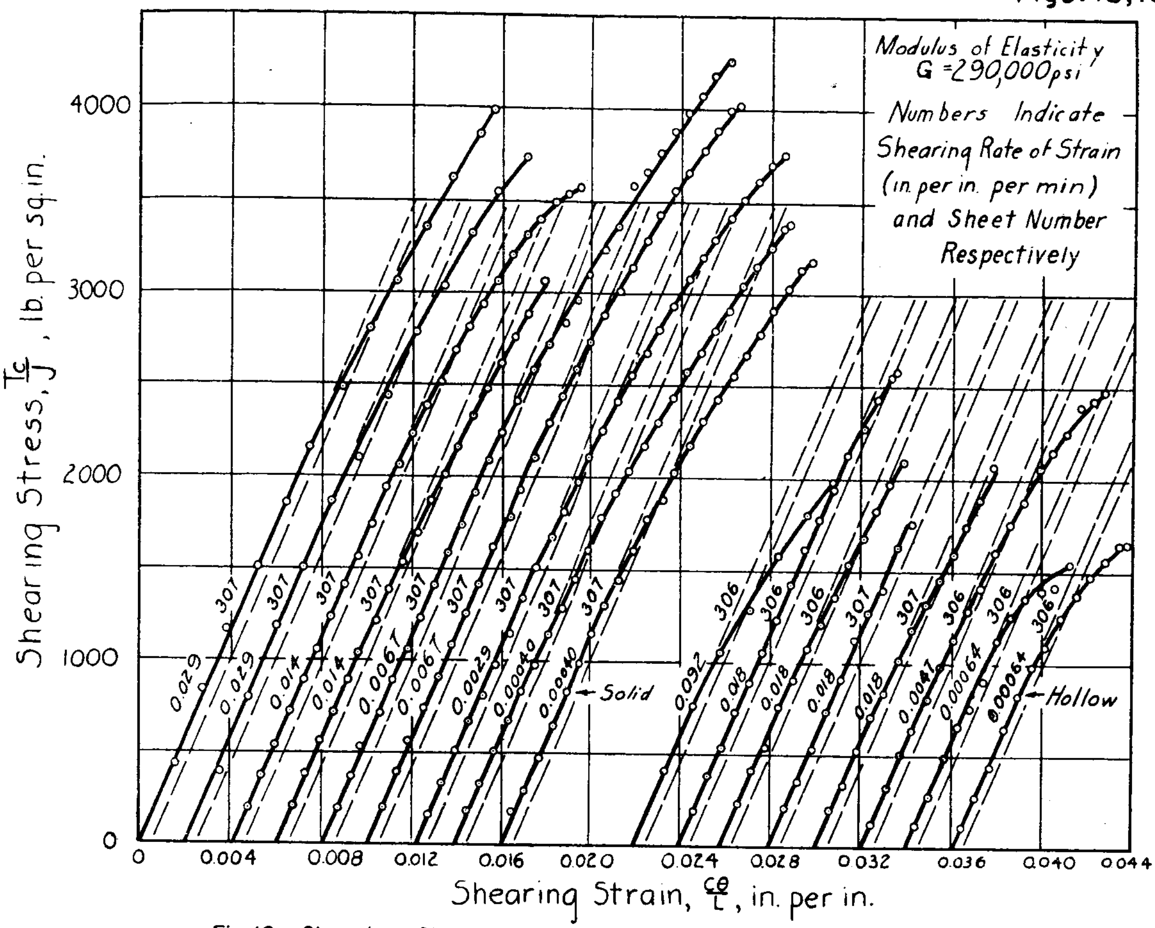

Fig. 18.- Shearing Stress vs Strain for Torsion of Solid and Hollow Specimens at Different Rates of Strain (Specimens Fig. 2e,f)

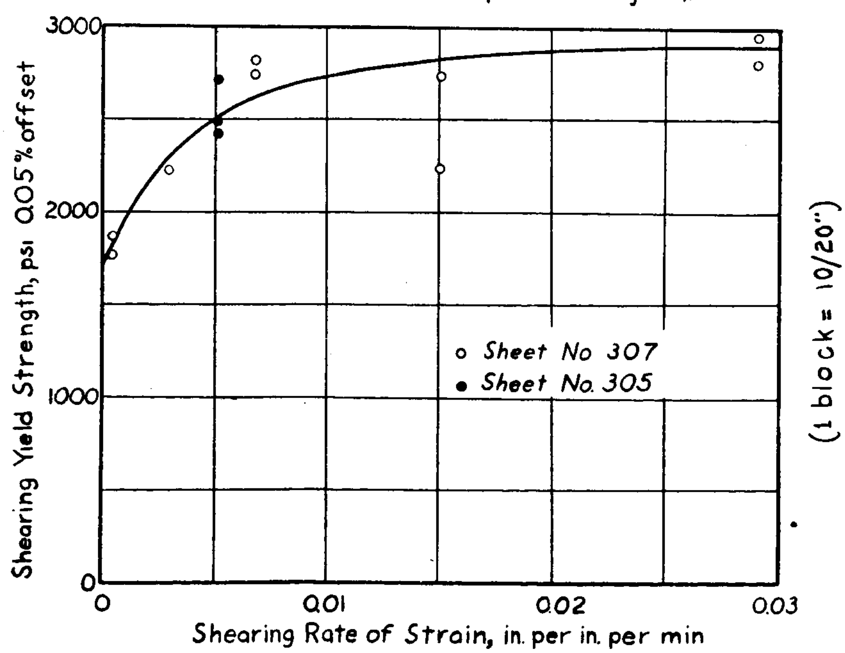

Fig. 19.- The Effect of "Speed" of Testing on the Yield Strength in Torsion at 0.05 per cent Offset

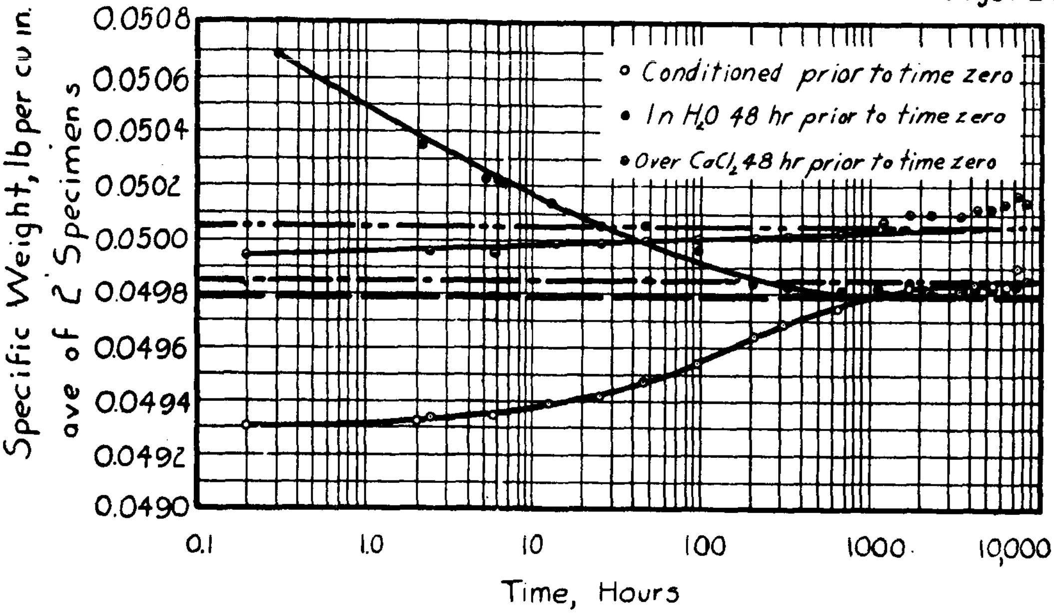

Fig. 20 The Effect of Initial Moisture Content on the Specific Weight after Different Intervals of Time at Constant Temperature and Relative Humidity (semi-log)

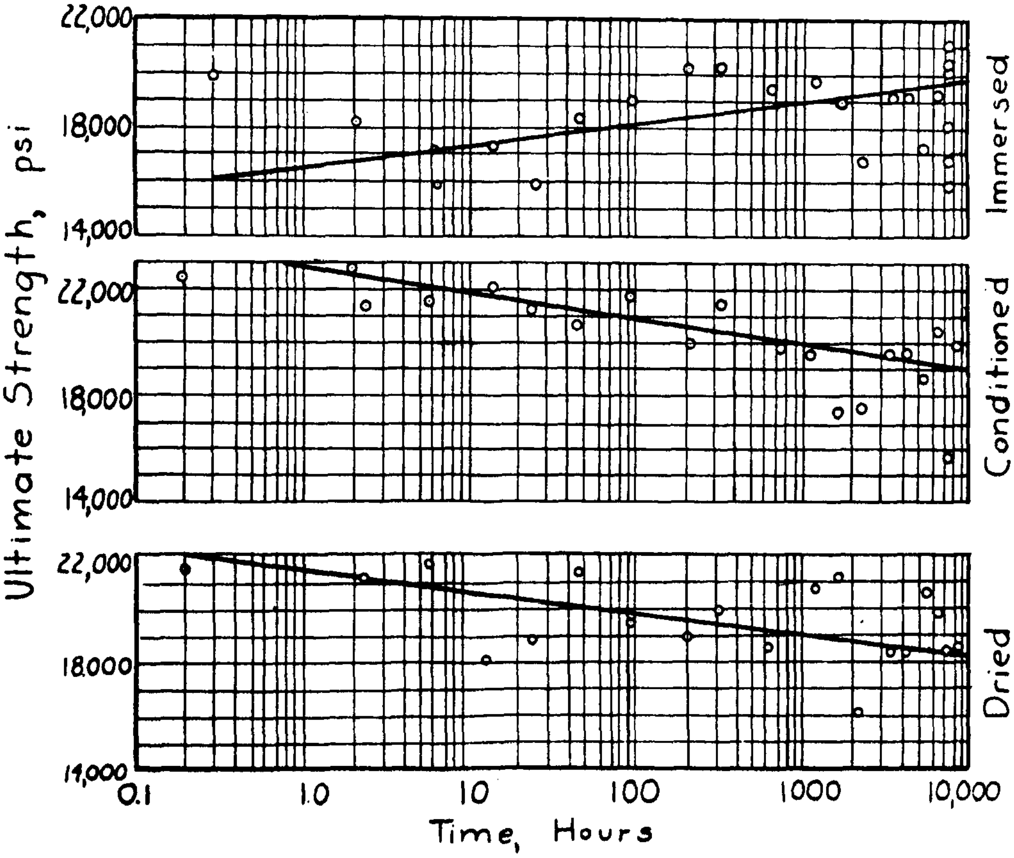

Fig. 21 The Effect of Initial Moisture Content on the Compressive Strength after Different Intervals of Time at Constant Temperature and Relative Humidity (semi-log)

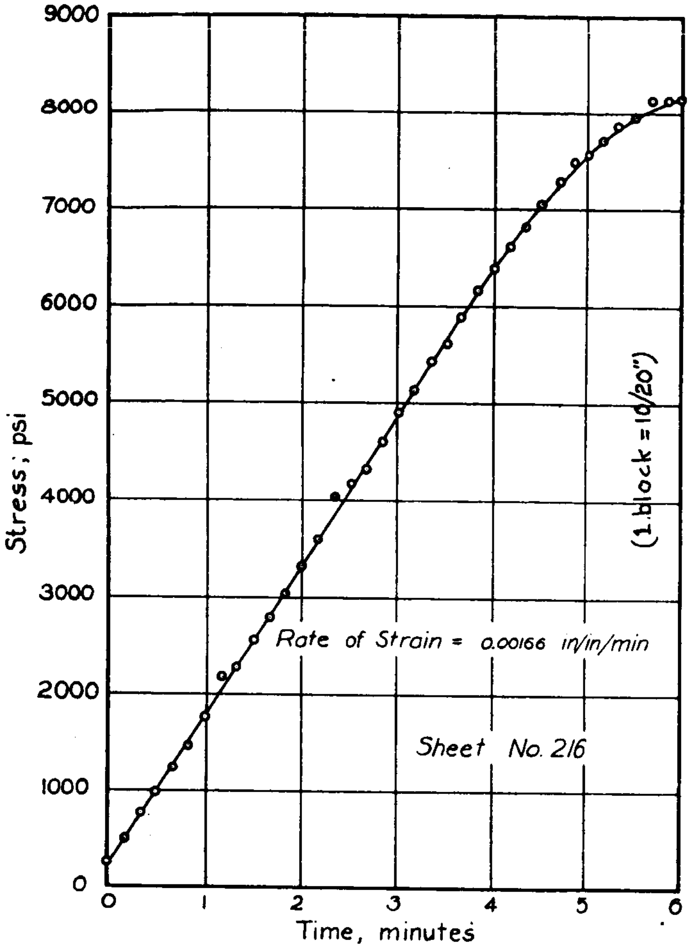

Fig. 22.- Stress vs Time in Bending
(Four Point Loading)

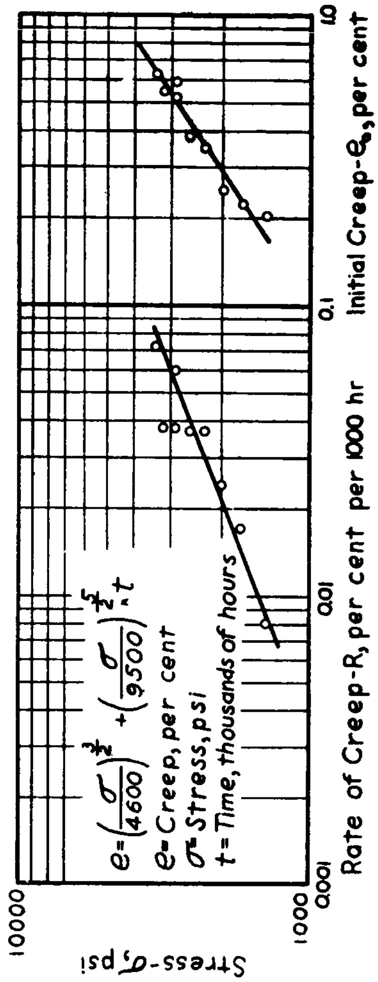

Fig. 25.- The Effect of Stress on the "Initial" Creep and the Rate of Creep (log-log)

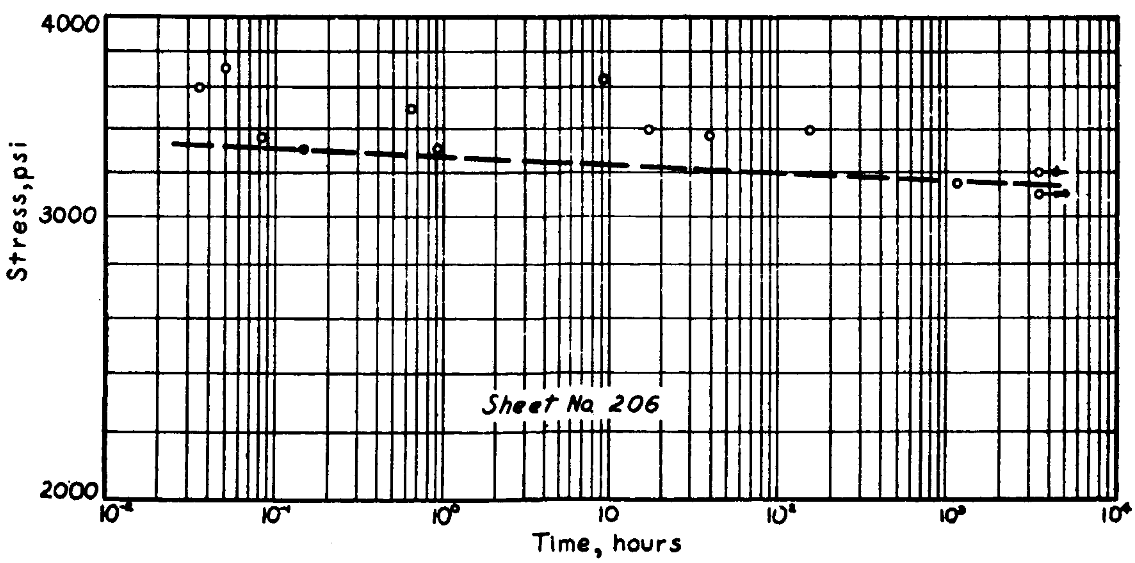

Fig. 26.- The Effect of Time of Application of a Constant Load on the Stress Causing Fracture (log-log)

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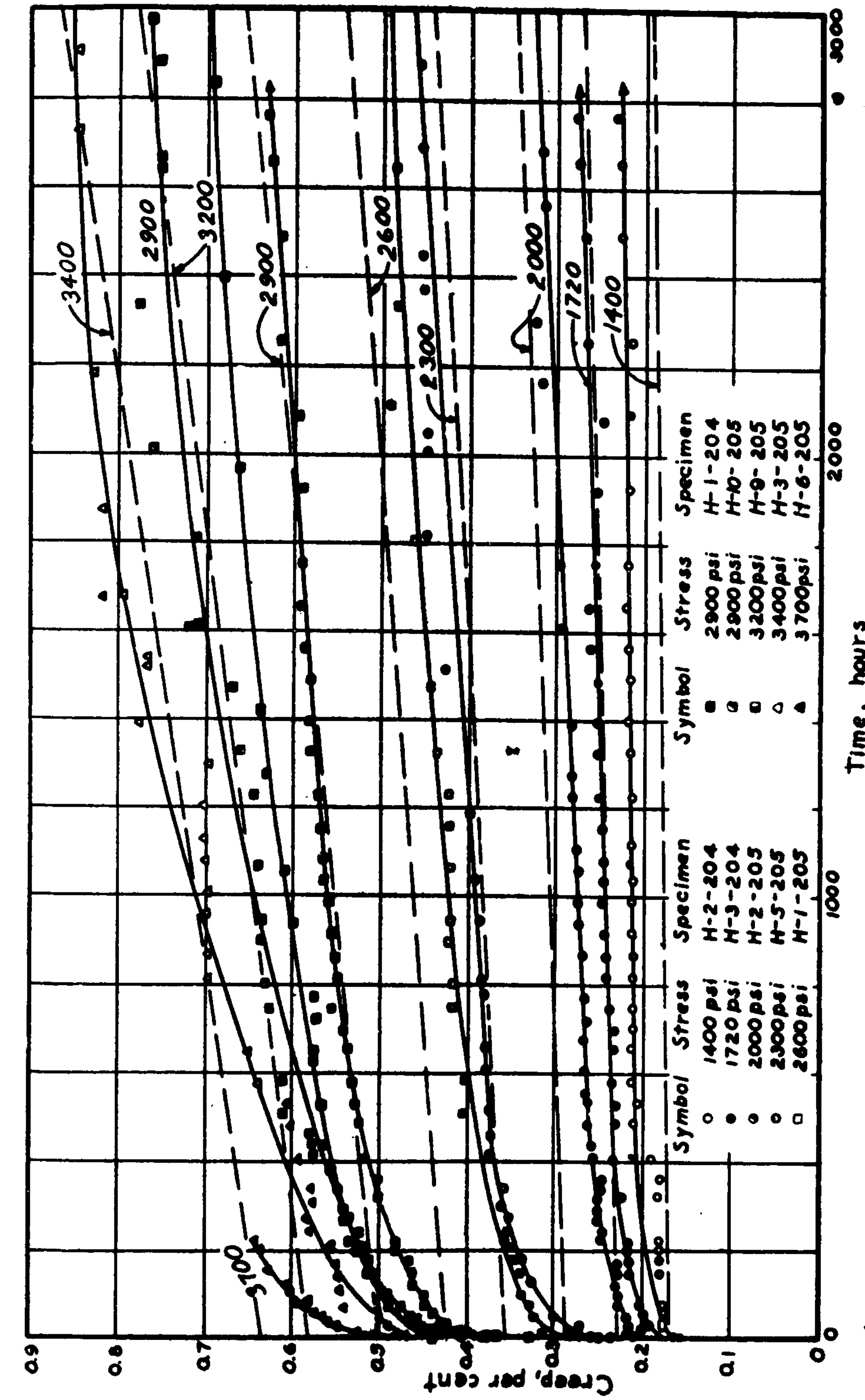

Fig. 23: Creep vs Time for Several Stresses, 3000hr

(1 block = 10/20")

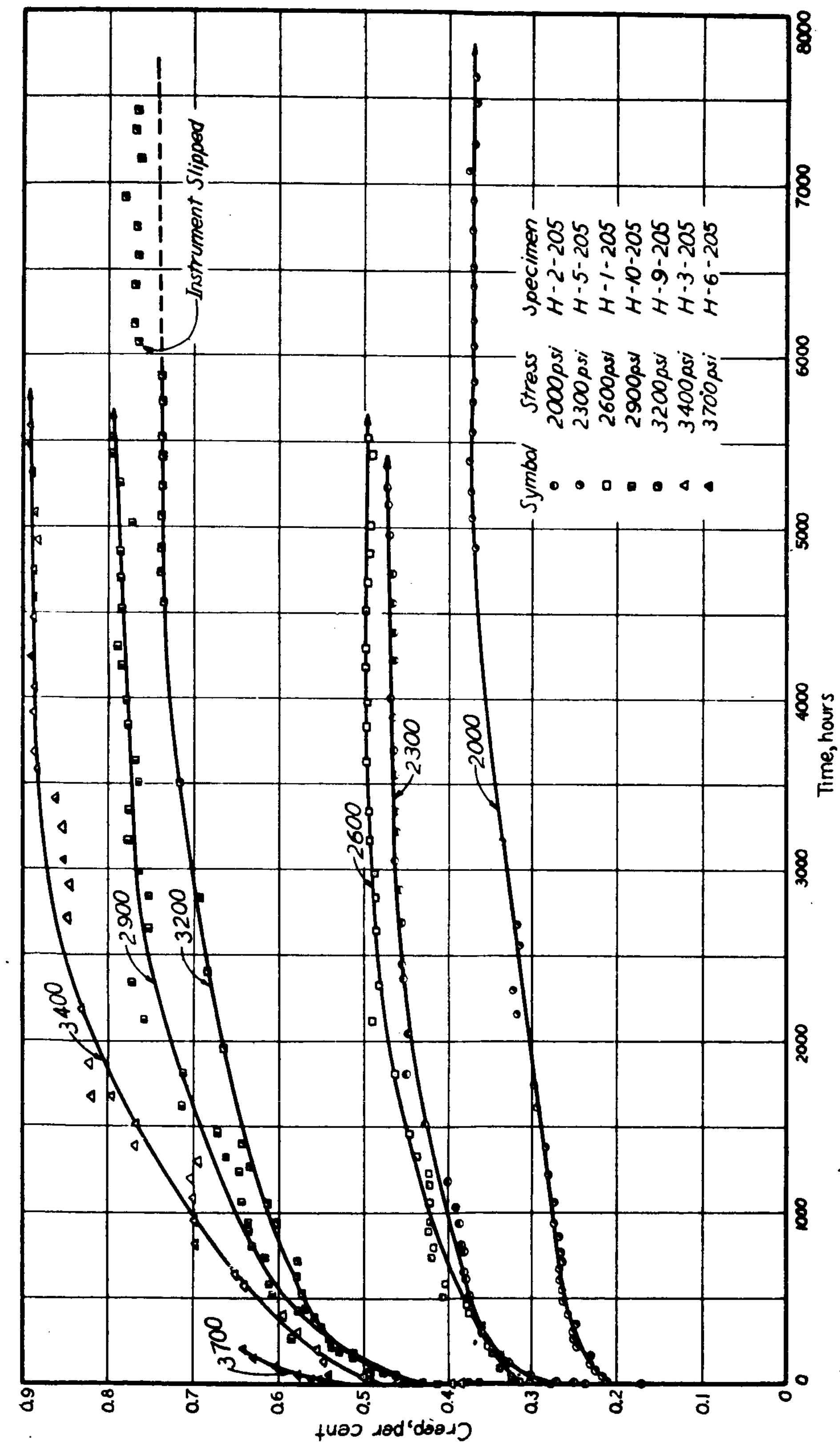

Fig. 24-Creep vs. Time for Several Stresses, 8000 hr.

(1 block = 10/20")

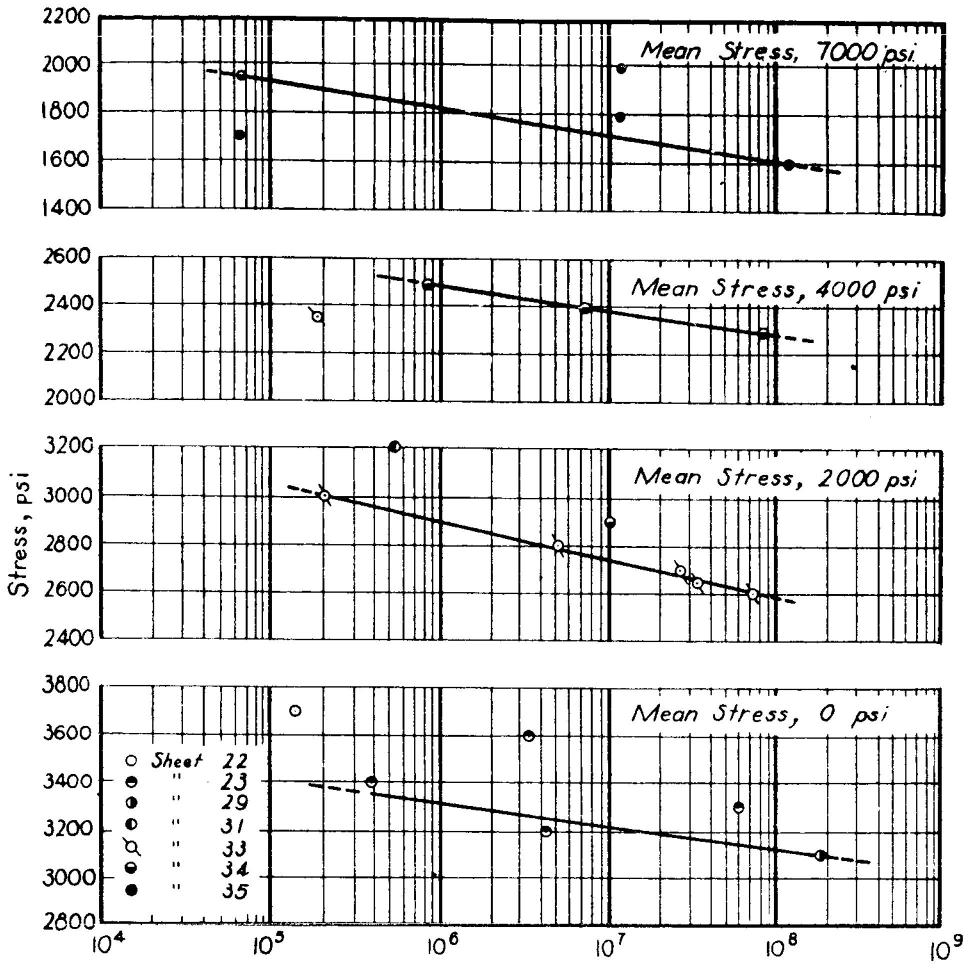

Fig.27.- σ-N Diagrams for Fatigue Tests at Several Different Values of Mean Stress (Machine - Fig.9, Specimen - Fig. 3a)

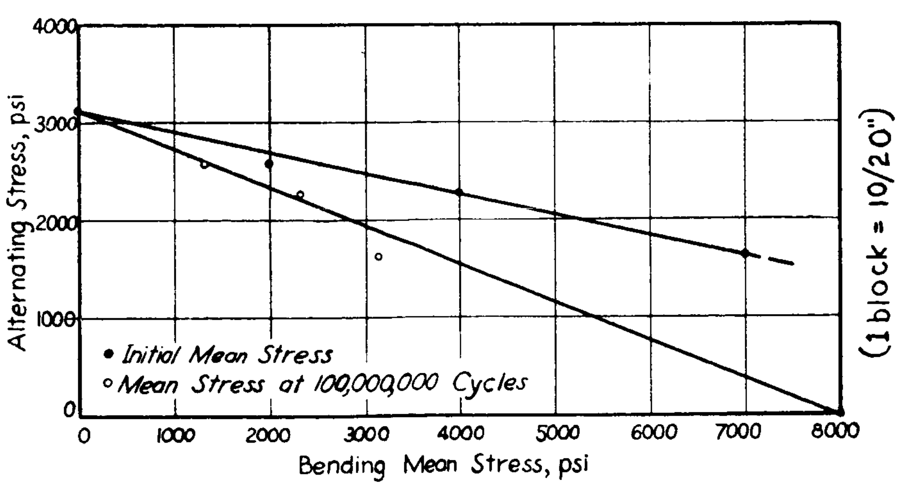

Fig. 28.-The Effect of Mean Stress on the Fatigue Strength at 100,000,000 Cycles

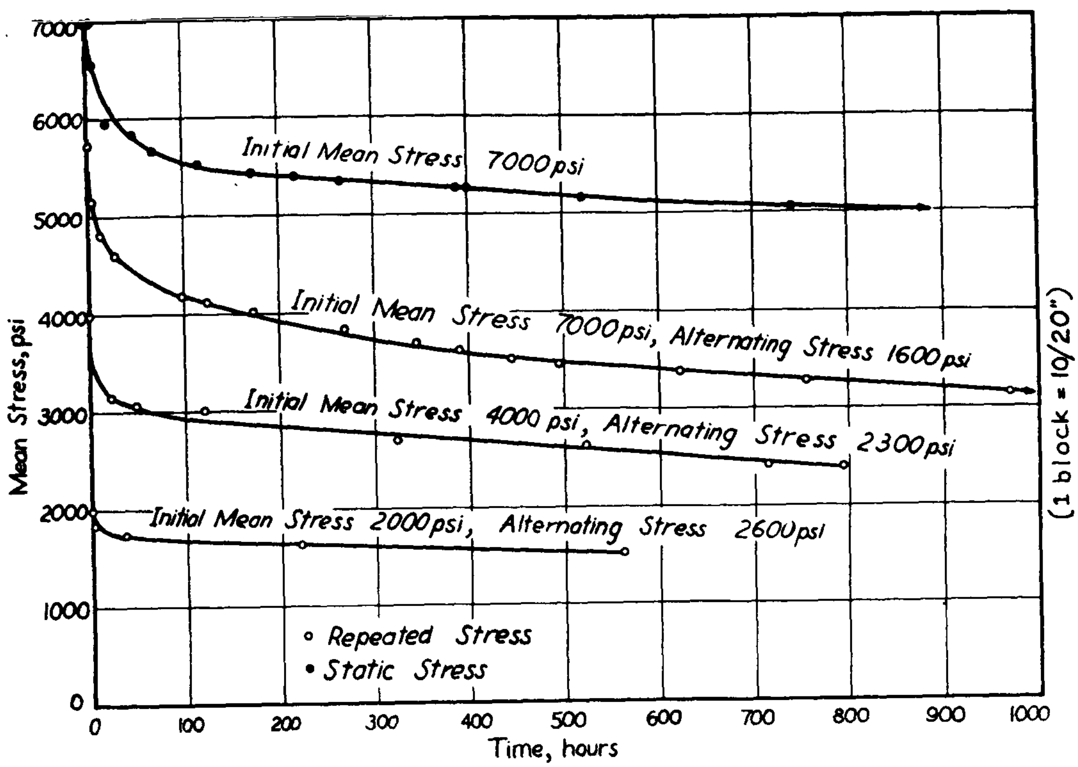

Fig. 29.- The Effect of Mean Stress and Repeated Bending on the Relaxation Under Constant Mean Deflection

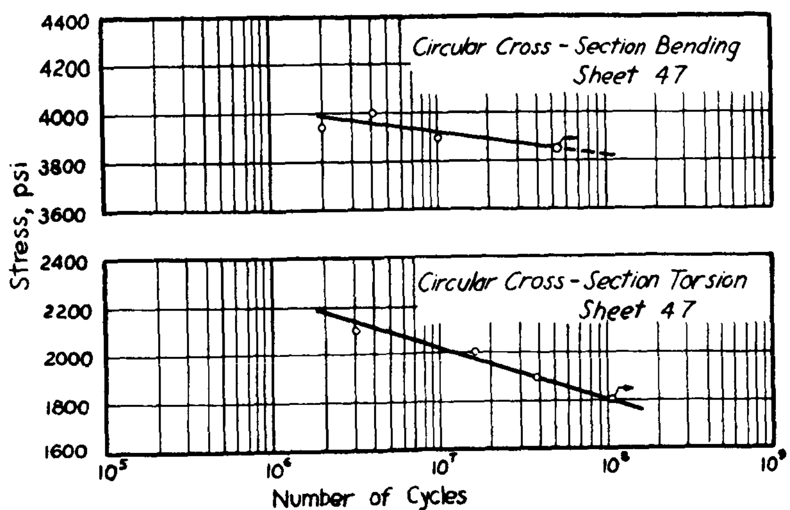

Fig. 30.- σ-N Diagrams for Torsion Fatigue and Bending Fatigue of Specimens of Circular Cross-Section (Machines Fig. 9 & 10, Specimen Fig. 3b)

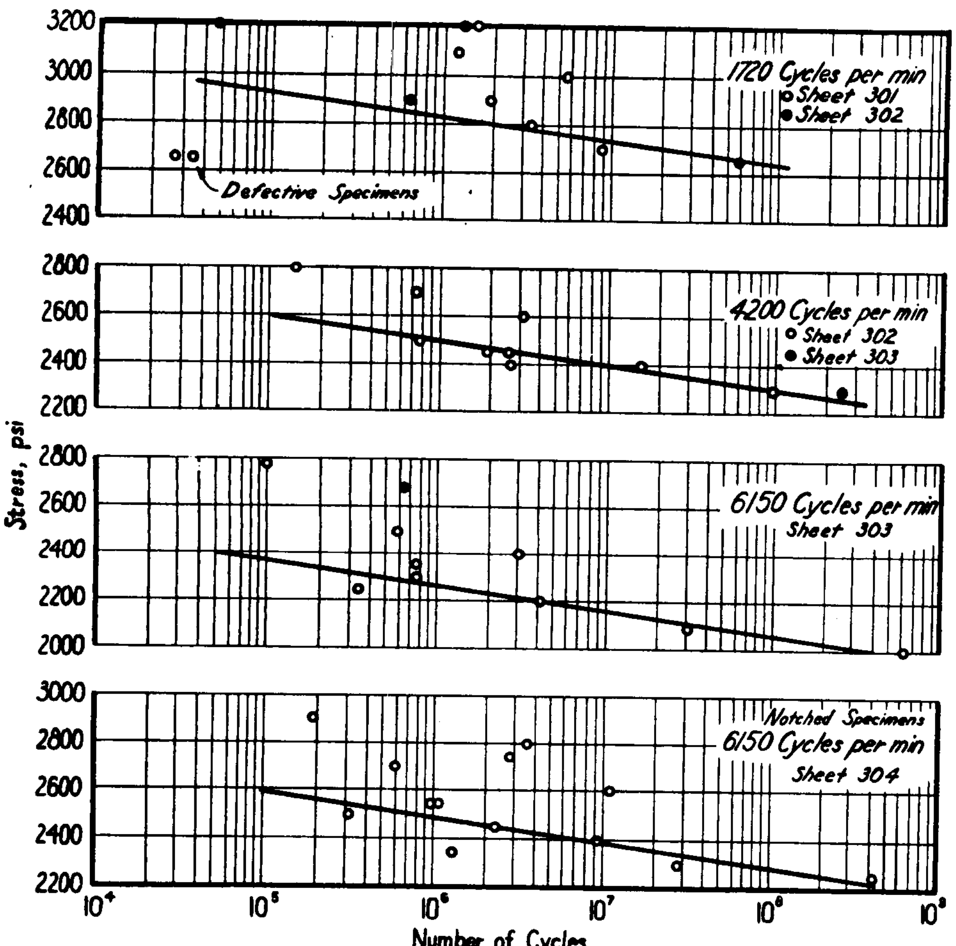

Fig. 31.- σ-N Diagrams for Rotating Beam Fatigue Tests of Notched Specimens and Unnotched Specimens at Several Different Testing Speeds (Machine Fig. 11) Specimens Fig. 3 c,d

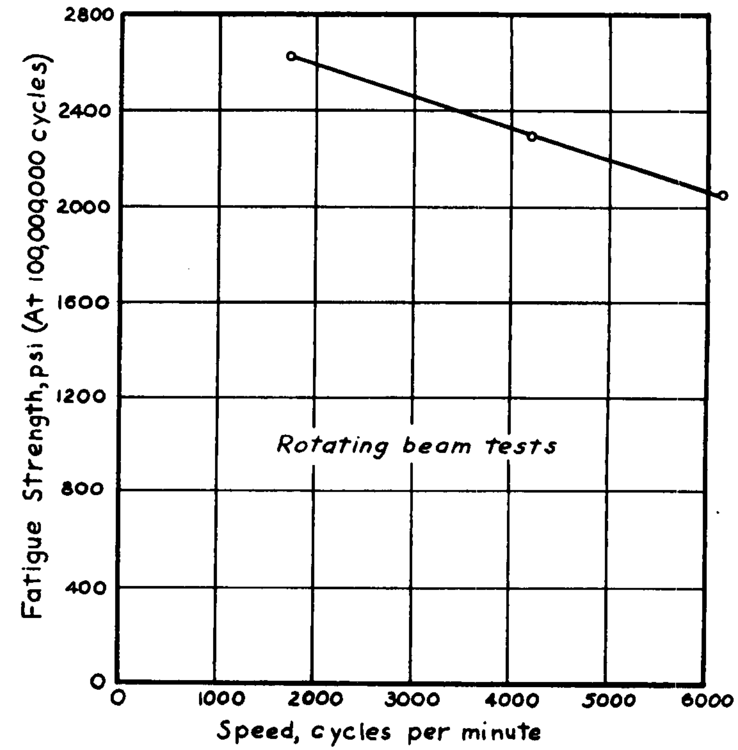

Fig. 32.- The Effect of Speed of Testing on the Fatigue Strength at 100,000,000 Cycles (Rotating Beam Machine)

(1 block = 10/20")

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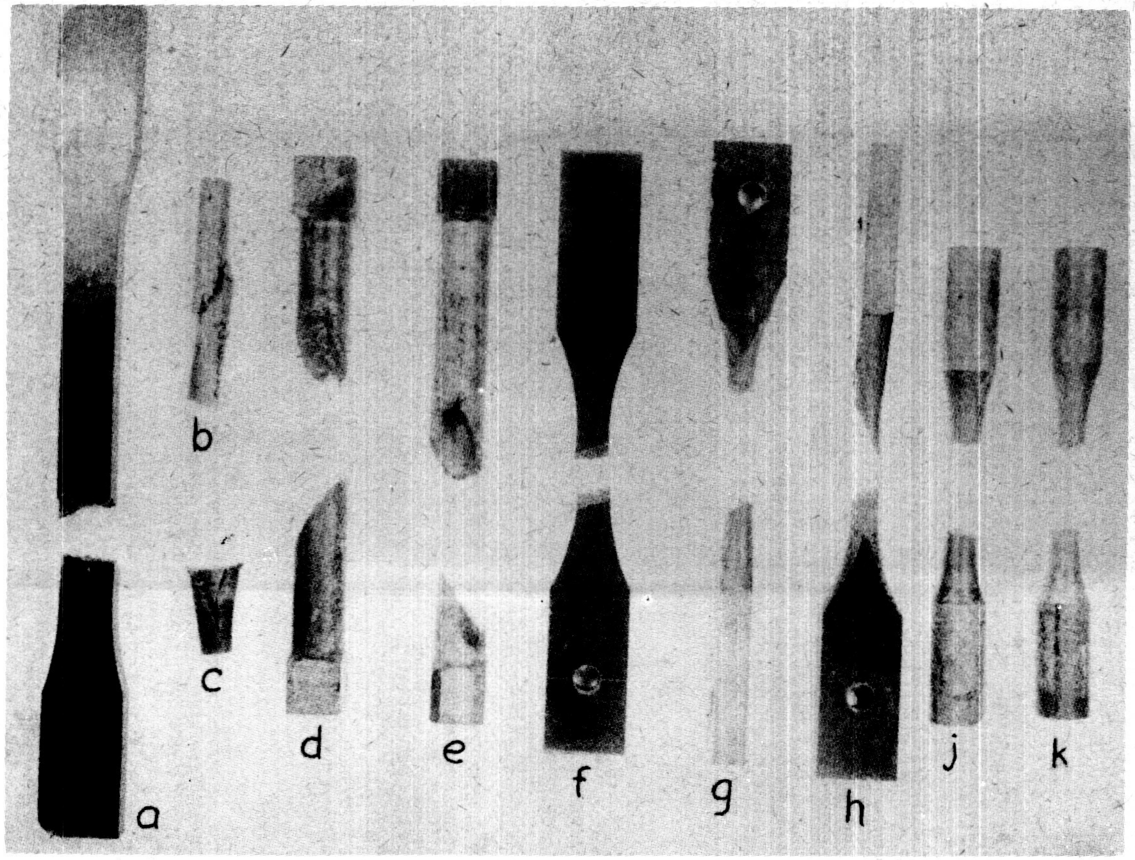

(a) Tension
(b) Long compression
(c) Short compression
(d) Solid torsion
(e) Hollow torsion
(f) Square fatigue
(g) Round bending fatigue
(h) Round torsion fatigue
(j) Notched rotating beam fatigue
(k) Rotating beam fatigue

Figure 33.- Fractured specimens.